Storm Surges in Tauranga Harbour

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Abstract

Understanding the potential elevation of extreme sea-levels at the coast is important for management of hazards, and adaptation to climate change. This poses challenges for coastlines around the globe, with current pressure from sea-level rise and predictions for an increase in the frequency of extreme events, storminess and associated storm surge hazards. Therefore present day extreme sea-levels are likely to occur more frequently in the future, reaching higher elevations. The largest storm surge on record in New Zealand was 0.88 m in Tauranga Harbour during Tropical Cyclone Gisele in 1968. This is lower in comparison to the tide which can be up to 2 m, therefore it is important to consider the role of storm tides on extreme sea-levels in New Zealand.

The main aim of this research is to understand how storm conditions amplify the sea-level variations across Tauranga Harbour. This is one of the first studies that aims to understand how storm conditions amplify the sea-level in the upper regions of the Harbour, and therefore affect the hazards in this zone. The peaks over threshold method was applied to sea-level data at four gauges inside the Harbour, and one on the open coast at Moturiki Island. Extreme storm surges were found to be influenced by the morphology of the coastline, and are largest at Omokoroa. Due to relatively short sea-level records, additional techniques using oral histories and photographic evidence provide additional data which can be used to validate results from extreme value analyses. Storm surge is variable depending on the intensity and track of significant storms relative to Tauranga Harbour.

On the 5th January 2018 a sub-tropical storm passing over Tauranga, coincided with king tide conditions, causing significant inundation around Tauranga Harbour. The event produced maximum recorded storm surge of 0.64 m at Hairini, with an estimated average recurrence interval of 100 years at this sea-level gauge. The combination of storm tide and wave run-up was highest around the southern entrance, indicating significant external wave energy entered the Harbour. This

event is an important reminder to monitor weather conditions closely during periods of king tide conditions.

Stepwise regression was also applied to determine the variance in storm surge explained by atmospheric pressure and wind. Atmospheric pressure explains approximately 50% of the variance in storm surges. Wind from the east was found to explain an additional 3 to 15% of the variance, with the most influence at Omokoroa as it experiences large fetches from the east, being located on the north eastern side of the Peninsula. Waves likely explain the remaining variance in storm surges which is supported by findings from historical events in this study, however further research is needed to quantify the effect of waves. The relationship between storm surge frequency and magnitude with the Southern Oscillation Index was investigated at Moturiki, due to the potential for increased coastal hazards during La Niña. No statistically significant relationship was identified, however the results indicate larger, more frequent surges during La Niña. Since 2012, there has been a greater frequency of storm surge events per year exceeding 0.4 m. This may be the result of the Interdecadal Pacific Oscillation which shifted around 2000, and was predicted to increase the storm surge hazard for several decades based on previous research.

The research provides information and data on sea-levels and storm surges which will be useful in the implementation of the King Tides Project in Tauranga Harbour. This is a tool primarily focused on engaging the community with sea-level related information and coastal hazards, which is crucial for increasing awareness and our ability to adapt to coastal hazards.

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Chapter One

Introduction

1.1 Overview

Storm surges are common coastal hazards around the world which can cause massive amounts of destruction and loss of life. They involve the temporary rise or fall in sea-level forced by a change in atmospheric pressure and wind (Pugh, 1987). A fall in atmospheric pressure associated with a low pressure weather system, combined with onshore winds will result in a positive storm surge and higher sea-level at the coast. Storm surges in New Zealand are generally lower compared to areas near the equator; however surges still pose a significant threat to low-lying land (de Lange & Gibb, 2000). In New Zealand, the largest storm surge on record was 0.88 m recorded at Sulphur Point in Tauranga Harbour, during Tropical Cyclone Gisele on 10th April 1968. The range of tidal elevations are larger, being up to 2 m during spring tide conditions (Heath, 1976; Stephens, 2015). Therefore it is important to consider the role of storm tides on extreme sea-levels around New Zealand. The main focus of this research is to understand the nature of extreme storm surges and how they change over spatial and temporal scales within and around Tauranga Harbour.

Storm surge observations in New Zealand are generally restricted to short sea-level records, and therefore historical records may include larger events than what exists on gauge records (Goring, Stephens, Bell & Pearson, 2010). Extreme value techniques can be applied to data of unusually high or low levels to predict their rate of occurrence (Coles, 2001). Numerous extreme value techniques have been applied to sea-level data in Tauranga Harbour and on the open coast at Moturiki in order to define the extent of coastal hazard zones. In the Bay of Plenty (BOP) region the minimum building level in 1962 was 2.5 m above MSL MVD-53 (Bay of Plenty Times, 10 July 2000). This was later raised by Gibb (1997) to 3.2 m, and lowered again in 1998 by the Council. The 1998 review of the work was carried out by Tonkin & Taylor which found that coastal inundation is more likely to occur on exposed low-lying land with shallow water depths, in comparison to sheltered locations with deeper water. The hazard level was subsequently lowered to between 2.7 m to 2.9 m based on location. The main concern which lead to the Council to fund this research was based on the likelihood of variability in extreme sea-levels around different parts of Tauranga Harbour.

The purpose of this work is to provide information on extreme sea-levels caused by storm surges in Tauranga Harbour. The drivers of storm surge are also studied along with their dependence on the Southern Oscillation Index (SOI). This is to enhance our understanding of storm surges and the processes causing their variability in Tauranga Harbour. Climate change is predicted to increase coastal hazards including sea-level rise (SLR) increased storminess and higher rainfall which will influence the extent of extreme sea-levels at the coast (Stephens & Bell, 2015).

1.2 Research Aims and Objectives

The main aim of this research is to understand how storm conditions amplify the sea-level variations across Tauranga Harbour. Multiple approaches, including extreme value analysis of sea-level data and collecting oral histories, are undertaken to estimate probability statistics (return periods) for individual extreme events. The main objective is to improve our understanding of areas around the Harbour that are vulnerable to coastal inundation, and verify these with existing data. This work is critical to Council planning to allow adaptation to future climate change. Tauranga Harbour has been a focus area for scientific research; however this is one of the first studies that aims to understand how storm conditions amplify the sea-level in the upper regions of the Harbour, and therefore affect the hazards in this zone. The research also aims to set up the groundwork for implementing the King Tides Project within the Harbour, following on from initiatives at Auckland Regional Council. The King Tides Project is a tool to engage and inform the community about coastal inundation and SLR, while providing crowd-sourced data for future hazard assessments (Roma´n-Rivera & Ellis, 2018). On the 5th January 2018, a sub-tropical storm coincided with king tide conditions, causing significant inundation around Tauranga Harbour. Chapter 5 covers detailed analysis and discussion for this event.

1.3 Study Area: Tauranga Harbour

Tauranga Harbour is classified as a tombolo island, barrier enclosed, meso-tidal estuary (Tay, Bryan, de Lange & Pilditch, 2013) (Figure 1-1). It occupies a large area, covering 218 km^2 (Bay of Plenty Regional Council, n.d.). The barrier was built from sand, supplied by a combination of onshore transport and longshore drift. Two stable Holocene barrier tombolos have fixed the location of the two inlets, and resulted in unique tidal dynamics, including estuary flushing. These include Mount Maunganui at the southern entrance (Tauranga basin) and Bowentown at the northern entrance (Katikati basin) separated by Matakana Island, a 24 km sand barrier (Davies-Colley & Healy, 1978). The southern entrance is approximately 35 m deep and 500 m wide, with an ebb tidal delta extending 3.5 km seaward (Spiers, Healy & Winters, 2009). The Harbour contains two connected basins which are separated by a large tidal flat which allows research to be focused within specific basins. The sea-level gauges used in this study are located within the southern basin of Tauranga Harbour and on the open coast at Moturiki Island.

Estuary classification in New Zealand was carried out by Hume & Herdendorf (1988) which provides useful estuarine information that can be used for resource management. Tauranga Harbour is classified as a category F estuary, with 14% of estuaries falling into this type in New Zealand (64 total). This type of estuary is characterised by lower freshwater inputs and larger tidal influences. They are usually well mixed and salinity stratification is only observed up some headwaters (some flooding can increase stratification further into the estuary). At low tide, the narrow channels drain large areas of gently inclined intertidal flats. Tidal flats cover 41 km^2 and are largely exposed during low tide, with a 2 m range in spring tide elevations (Heath, 1976). It is one of the largest estuaries in New Zealand and has been a strong research focus, with high commercial and recreational demands (Tay et al., 2013). The largest port in the country is located in the southern basin, with coastal development increasing around the catchment largely from the 1960s.

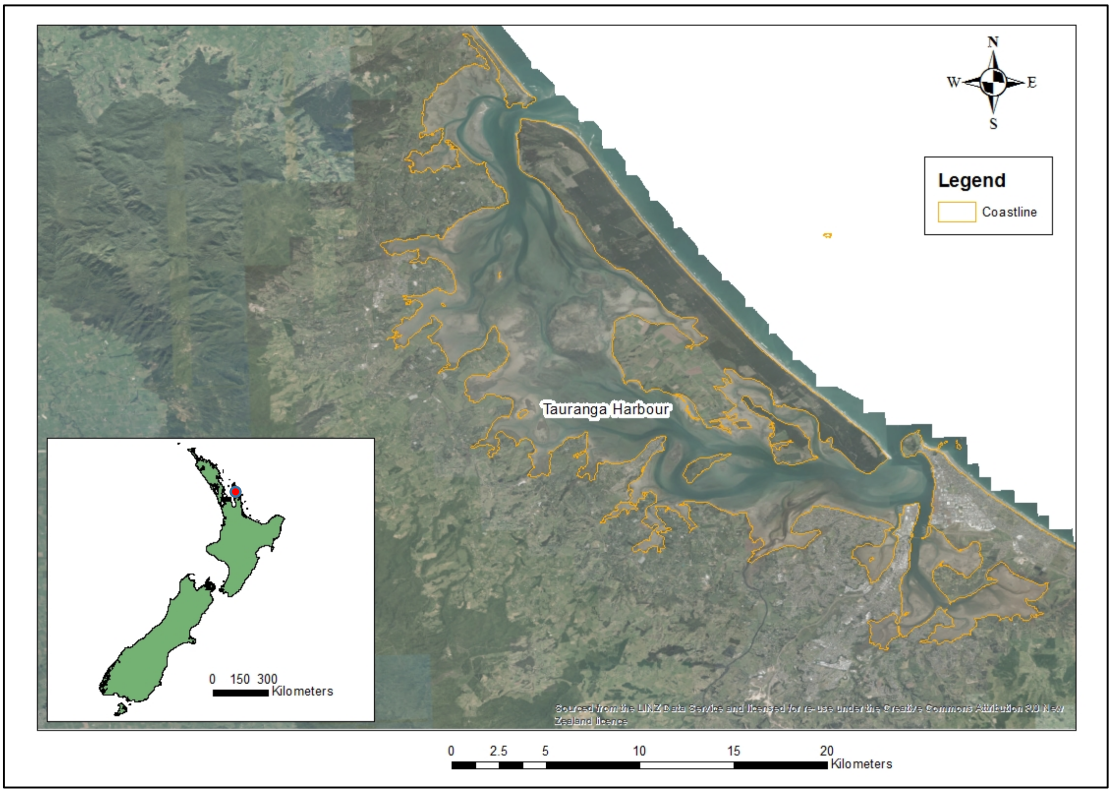

Figure 1-1-Aerial image of Tauranga Harbour.

1.4 Thesis Outline

- In Chapter 2, the literature on estuaries, sea-level, storm surges and extreme value techniques are discussed, with an emphasis on New Zealand.

- In Chapter 3, the extreme value analysis is applied to sea-level data. Results and discussion are included within the Chapter.

- In Chapter 4, additional methods are used to reconstruct extreme sea-levels in Tauranga Harbour. These include the use of oral histories, newspapers and photographic evidence.

- In Chapter 5, a detailed analysis and discussion of the event on 5th January 2018 which caused significant coastal inundation around Tauranga Harbour.

- In Chapter 6, the drivers of storm surges are investigated to determine how much storm surge variance are explained. Further analysis of storm surge at Moturiki investigates the frequency and magnitude of surges and whether they are related to the Southern Oscillation Index (SOI). This work carries on from previous studies (de Lange & Gibb, 2000; Goring, 2006).

- In Chapter 7, a general discussion and conclusion is provided, based on the overall aims and objectives. Limitations and future research ideas are also discussed.

Chapter Two

Literature Review

2.1 Estuaries

Estuaries are important natural resources which provide society with a place for commercial and recreational activities (Hume & Herdendorf, 1988). They are dynamic landforms subject to a variety of forces, dominated by catchment and coastal processes. Estuary classification by Hume and Herdendorf (1988) in New Zealand has enhanced coastal resource management by providing a good source of estuarine information. The most widely applied definition of an estuary was from Pritchard, stating they are semi-enclosed bodies of water at the coast which are connected by an area of free flowing water to the open ocean, and where freshwater from catchment drainage has impacted the salinity. A more accurate definition was then put forward by Day as a, "partially enclosed coastal body of water which is either permanently or periodically open to the sea and within which there is a measurable variation of salinity due to the mixture of seawater and freshwater derived from land drainage" (Hume & Herdendorf, 1988, p. 250). This change in definition was driven from coastal lagoons and hypersaline water bodies which were not incorporated for by Pritchard. Estuaries have been classified into five different groups based on the main processes which shaped their basins. These include fluvial erosion, marine/fluvial erosion, tectonic, volcanic and glacial. Tauranga Harbour is an estuary which has formed by fluvial erosion (Hume & Herdendorf, 1988). This is where river action cuts out the depositional basin, usually at a time when sea level was lower than present. Sea level rise has then covered these cut out areas and the estuary has been altered yet again from sediment deposition (fluvial and marine processes).

2.2 Storm Surges

The combination of pressure (low atmospheric), and wind stress during storms can result in raised water levels at the coast, known as storm surges (Pugh, 1987). Maximum water levels are reached during dynamic wave set-up. Storm surges can be positive or negative. In the Bay of Plenty (BOP) Region, a drop in pressure, combined with onshore or longshore winds up the coast (approx. north-west direction), can result in a positive storm surge. A negative storm surge can occur following an increase in pressure with offshore winds or longshore winds down the coast (approx. south-east direction). Speer & Aubrey (1985) showed that in a choked lagoon, storm surges can have a significant influence on sea-level variability.

2.2.1 Storm Surges in a Global Context

Coastal hazards from storm surges are considerably lower in New Zealand mainly because storm surge atmospheric processes are more intense near the equator (de Lange & Gibb, 2000). In Bangladesh, storm tides have killed more than 700,000 people since 1960 (Lewis, Schuman, Bates & Horsburgh, 2013). The risk from flooding in Bangladesh is high due to the geomorphology and effects from bathymetry which increase storm surge amplitudes along low lying regions with large populations. When compared to the Gulf Coast (USA), or the Bay of Bengal, New Zealand storm surges have smaller elevations but a higher occurrence (Hume, Bell, de Lange, Healy, Hicks, & Kirk, 1992). They are still a natural hazard which causes inundation and erosion along large sections of New Zealand coastline (lower gradient shorelines). They are significantly enhanced where large shallow areas occur offshore, enhancing the stress from wind, including Tauranga Harbour (de Lange & Gibb, 2000).

de Lange (1983) noted that a number of historical tidal wave reports were most likely storm surges instead, with the largest measured storm surge in New Zealand being 0.85 m, triggered by Cyclone Giselle in April 1968 (Stephens, 2015). This is smaller in elevation compared with high tides which average 1 m above mean sea level, and can be up to 2 m during spring tide conditions. Therefore in New Zealand it is important to consider the role of both tides and storm surges, commonly referred to as storm tides.

2.2.2 New Zealand Sea-levels

In New Zealand, sea-level rise (SLR) has been occurring since the 1800's. Long term sea-level records are generally more sparse in the Southern Hemisphere, including New Zealand, which has four main data sets from ports around the country (Hannah & Bell, 2012). These include Auckland, Wellington, Lyttelton and Dunedin. Due to short sea-level records in Tauranga Harbour, SLR estimates can be taken from the nearest long term sea-level records at the Port of Auckland, which started in 1899 (Bell, Goring, Gorman, Hicks, Hurran, & Ramsay, 2006). This has shown a rise of 0.14 m over the last century. The global rate has been between 0.1 m to 0.2 m, with New Zealand averaging 0.16 m. Due to climate change, processes such as sea surface temperature, thermal expansion and glacial melting are all predicted to enhance rates of SLR into the future.

The maximum water level at or close to high tide during a storm tide is the consequence of sea level anomaly (SLA), tide and storm surge processes. For long term coastal planning, an appropriate rate of sea level rise (SLR) has been defined as 1 m (for the year 2115) (Stephens, 2015). The Intergovernmental Panel on Climate Change (IPCC), "business as usual" report has considered sea level rise of 0.33 m by 2070 under the Representative Concentration Pathway (RCP) 8.5 median SLR trajectory, or by 2090 under the RCP2.6 median (low green house has emissions).

2.3 Vertical Land Movement

Vertical land movements (VLM) can impact relative (local) sea level (Bell et al., 2006). For example SLR and coastal hazards are greater in areas where land at the coast is subsiding. Likewise if the land is being uplifted, local SLR and coastal hazards will be reduced. If uplift exceeds the rate of SLR, then relative sea-level can be seen as falling. In the BOP, tectonic movements have been occurring however the area between Waihi and Papamoa (including Tauranga Harbour) are reasonably stable (Stephens, 2017). Over a 9 year period, the Papamoa hills experienced VLM rates measuring +0.5 mm/y (Beavan & Litchfield, 2012; Houlie &

Stern, 2017). From 2003 GeoNet and Land Information New Zealand (LINZ) have implemented GPS locations which monitor land movements.

2.4 Climate Change

Water level peaks occur 706 times per year in New Zealand (Stephens, 2015). This is the result of the semi-diurnal tide (M2 lunar-two times daily), with a 12.42 hour period, which results in high tide occurring somewhere along the coast at any given time. Albrecht & Vennel (2007) highlight the dominant M2 tidal component in two constricted lagoons in New Zealand with mixed semidiurnal tides. The M2 tide is dominant in Tauranga Harbour. Coastal inundation and erosion are hazards which result from a combination of factors, specifically extreme weather conditions and climatic variations. Through climate change, it is predicted that these drivers of natural hazards will be increased, posing larger threats to the coastal environment (sea-level rise, increased wind and rainfall, and greater storm tides) (Stephen & Bell, 2015). Natural causes and hazard drivers for coastal inundation are also influenced by climatic variations including the El Niño-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (Bell et al., 2006).

2.5 Tides

The theory of harmonic analysis was established in 1868 by Lord Kelvin, and was improved in 1883 by Darwin (Parker, 1984). The tide can be divided into tidal constituents which have amplitudes and phases that can be predicted from observations of previous tide time series, known as tidal harmonic analysis. The movements of the Earth, Moon and Sun make up the important periods and allow the tide to be predicted at any location (if observations were carried out). The Moon comprises the majority of the tide generating force, with the Sun contributing only 46% of the Moons ability (Masselink et al., 2011). The Moons orbit around Earth is not circular but elliptical. This results in two lunar phases, the perigee which corresponds to the Moon being closest to Earth (357,000 km) and apogee when the Moon is furthest away (407,000 km). Therefore tidal elevations are increased slightly during perigee. The Moons orbital variation covers 27.6 days and is termed an anomalistic month. Perigean spring tides are the largest tides which result when the lunar perigee coincides with the new or full Moon, occurring approximately 3 to 4 times each year. These tides are slightly higher, generally up to a couple of inches compared to ‘normal’ spring tides. Spring tides are also higher around the months from November to March due to the earth orbiting closer to the sun (Woodworth & Blackman, 2004; Patel, 2006).

Water acceleration is influenced by pressure gradients, Coriolis, gravity and friction. The effect of friction in the tide has been a more recent discovery with the identification of linear terms along with inertial terms and non-linear terms. The non-linear frictional effects have recently been found to have just as much of an influence on water acceleration as, “shallow water” terms (nonlinear continuity and inertial (convective)) (Parker 1984). The tide acts as a shallow water wave, with speed calculated by equation 1.1:

$$c = \sqrt{gh} = \frac{L}{T} \tag{1.1}$$

Where *c*=speed, *g*=gravity, *h*=water depth, *L*=wavelength and *T*=wave period. Within estuaries the water level and direction of flow (horizontal) is controlled by tidal propagation (Masselink, Hughes, & Knight, 2011). For half the tidal period currents move landward, known as the flood tide. In comparison the other half tidal period is the ebb tide, where currents are moving seaward. Generally 1 to 2 hours after the change between these two periods, current velocity is reduced (slack tide) with the greatest currents occurring during mid-tide. The maximum tidal range occur at the location of antinodes, commonly found at the estuary head. Minimum tide ranges occur at the location of nodes, generally at the estuary entrance. Some estuaries will favour progressive tides or standing tides, but most will display a combination of both. Generally the tide will be more progressive closer to the entrance, with standing tides further toward the head where reflection is occurring (Masselink et al., 2011).

Channels within estuaries are generally more narrow and shallow away from the coast. This can result in reduced current velocities, changing the tidal wavelength (same effect as shoaling). Bed friction has been found to oppose the effects of shoaling and convergence, due to low frequencies (i.e. long wavelengths) (Parker, 1984). This influence is particularly significant between the channel and tide, reducing the tidal range through energy dissipation, and is larger in areas with increased tidal amplitude and decreasing water depths. This process can result in three possible scenarios for tides within estuaries:

1. Synchronous estuaries occur where effects from shoaling and friction are balanced, resulting in constant tidal range as you get further from the coast/entrance. At the tidal limit, friction overcomes shoaling and the range is reduced to zero.
2. Hyposynchronous estuaries occur where friction is the main factor (overcoming shoaling effects) over the entire estuary, decreasing the tidal range.
3. Hypersynchronous estuaries occur when shoaling is the main factor, overcoming frictional effects, resulting in amplified tidal ranges with further distance from the coast.

Towards the tidal limit, frictional effects take over and the tidal range is reduced to zero. Hypersynchronous estuaries are normally longer compared with short estuaries which are normally hyposynchronous, however synchronicity is largely influenced by the entrance conditions (Masselink et al., 2011). Tidal distortion is a common process in longer estuaries, generally showing shorter flood tides and longer ebb tides (asymmetrical wavelength). The wave front is steep as it propagates through the estuary. In deeper water offshore, the tidal range only accounts for a small percentage of the water depth, therefore the difference in speed between crests and troughs are minimal. Within estuaries, the tidal range can be a significant percentage of the water depth, and therefore deeper water beneath crests will travel faster compared to shallower water beneath toughs (Masselink et al., 2011). This can be demonstrated by rewriting equation 1.1 as equation 1.1.1:

$$c = \sqrt{g(\bar{h} \pm a)} \quad (1.1.1)$$

Where $\bar{h}$ = the local tidally averaged water depth, and a = the amplitude of the tide. In shallower water (<5m depth), the speed difference is increased at a rapid rate along with tidal distortion. At some locations, the distortion can be large enough to form vertical tidal fronts, similar to a breaking wave in the surf zone, referred to as tidal bores.

Probabilities of extreme sea levels can be determined by several different factors including tides, storm surges and mean sea-level. There has been a small amount of storm surge research in New Zealand, considering their frequent occurrence. Hume et al., (1992) reported storm surges in New Zealand of between 0.3 m to 0.88 m based on previous studies. The largest storm surge of 0.88 m was recorded at Sulphur Point in Tauranga Harbour during the passage of Tropical Cyclone Giselle during the 9th to 10th April 1968 (Gibb, 1997). The first compiled historical records were from the BOP region by Hay (1991), identifying 153 events from January 1873 to August 1990. It is recognised that the most intense historical storm surges and waves are triggered by tropical cyclones (generally ex-tropical cyclones when they reach New Zealand) and large wind storms from the north to north east (Heath, 1979; Hay, 1991; de Lange & Gibb, 2000). Most of these storms were defined by low atmospheric pressure recordings of between 995 hPa to 1005 hPa, fetches between 400 km to 500 km and durations of 6 to 39 hours (with one extreme event lasting 92 hours) (Hay, 1991).

2.6 El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) involves the exchange of large quantities of air between the eastern and western hemispheres (Trenberth, 1977). This is the result of changes in global pressure. The Bay of Plenty weather and climate is influenced by ENSO. A positive southern oscillation index (SOI) is defined as the La Niña phase, with negative index values defined as the El Niño phase. A strong La Niña is correlated with values above 1, and strong El Niño with values below 1. During El Niño in the BOP, the dominant wind direction is offshore from the south-west. This results in more negative surges and overall lowering of regional sea level along the east coast of northern New Zealand (Goring & Bell, 1999). During La Niña, increased north-east flows (onshore winds) and more frequent storms result in a temporary rise in regional sea-level along the BOP coastline (de Lange & Gibb, 2000). It should also be noted that the nature and strength of ENSO also changes at decadal periods from variations in the amplitude and period of its constituents (Wang 1995; Wang & Wang, 1996). Storm frequency and magnitude in the south west Pacific are influenced by this (Basher & Zheng, 1995) which effects the nature of ENSO in the BOP.

de Lange & Gibb (2000) found that atmospheric processes including seasonal changes, El Niño-Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO) influence the variability of storm surges in Tauranga Harbour. They analysed tide gauge data for the southern basin of the Harbour for the period between 1960 to mid 1988. Their findings showed that storm surge size and frequency were greater during 1960 to 1976, but then significantly reduced from 1976 to 1988 which was suggested to be a response to changes in the IPO (20 to 30 year cycle). From these findings it has been predicted that the increased storm surge amplitude and frequency will occur in the nearby future as a result of the IPO. ENSO also had an impact on storm surges, with higher frequencies occurring during La Niña phases (2-4 year cycle).

2.7 Extreme Sea-levels

Flood risk predictions and their accuracy depend on information of peak storm tide heights and their variability (Lewis et al., 2013). A common method has been to use inundation models, using depth averages from shallow water equations to predict the current and future flooding probabilities. Shuttle Radar Topography Mission (SRTM) terrain data has been useful for carrying out dynamic coastal inundation modelling in areas with lower quality data, but the level of error needs to be recognized (Lewis et al., 2013). Public data was used in the regional-scale model for coastal inundation in the northern Bay of Bengal, developed from the newest LISFLOOD-FP formula. This type of model is less costly (computationally) compared to hydrodynamic models (Bates, Horritt & Fewtrell, 2010). To minimize disturbances from noise (SRTM) and vegetation, the data was scaled from the original resolution of 90 meters to 900 meters. A sub grid was also installed/nested into the model to identify and simulate any channels with widths less than the resolution, representing six river flows in total. The model simulated the 2007 cyclone event, Sidr using two cyclone databases, with predictions being verified from the accuracy of the root mean square error (RMSE), as 2 meters, which was comparable to the error from water level forcing (Lewis el al., 2013).

Long term water level records are used to estimate extreme sea-levels with a given return period (probability of exceedance, such as the 1 in 100 year water level). Bathymetry and topography make the extreme water level more complex to quantify due to spatial variability (Lewis et al., 2013). Tide gauges are usually located in estuaries/harbours which have a higher level of protection when compared to the open ocean. This may somewhat reduce our understanding of tides at the coast due to the presence of bed friction, bathymetry, water level and other localised effects such as freshwater input (Hume et al., 1992).

Tide gauge records provide useful sea-level information, however records in New Zealand are mostly poor quality and only cover short time periods. Multiple methods have been implemented to obtain the most useful information from these data sets, including interpolation, filtering, and filling in gaps from photographic evidence and oral histories. A Monte Carlo joint-probability (MCJP) method was used to obtain extreme sea level predictions from short term tide gauge records (sampled at least every hour) at Moturiki Island for a 23 year period (Goring et al., 1997). This method used storm-tide components including tide, storm surge and sea level anomaly, making them independent from each other and randomly mixing them together (storm-tide sequence). They found that tidal constituents (M2, N2 and S2), made up 93% of the variability in sea level at this location. Storm surges accounted for 21% of the remaining 7%. To obtain the extreme sea level for a certain location, the time series data for each component is needed. An advantage of this method is that it provides flexibility when it comes to measuring and modelling the different components. Within the Waitemata, Manukau and Kaipara Harbours, the MCJP method has also been implemented. 10 components were calculated from tide gauge data, and areas away from gauges were calculated using hydrodynamic model simulations. This method for predicting inundation levels held up well in front of Hearing scrutiny, emphasizing its strength (Stephens & Bell, 2015).

The mean high water perigean spring elevation (MHWPS) has been used in New Zealand to define, “red alert” tide levels (Stephens, 2015). These are known for providing the highest tides, often referred to as king tides. This is important as the tide has the largest influence on sea level variability in New Zealand. Storm tides in New Zealand that have caused problems with flooding, usually involve the combination of a small to medium storm surge with a high tide and high background SLA. This started the basis for storm tide forecasting in New Zealand by the National Institute of Weather and Atmospheric Research (NIWA), which now provide a pre-published list every year on their website of, “red alert” days when high perigean spring tides are predicted.

Coastal Scientists and Hazard Managers (i.e. NIWA and Regional Councils) need to carefully watch weather forecasts to identify low barometric pressure systems and high winds that might coincide with these red alert days, potentially causing coastal inundation in vulnerable areas. In Auckland the storm surge that occurred on 23rd January 2011 caused several million dollars of damage from inundation which shut down the major highway. It was the highest recorded surge in this area since 1903 at only 0.4 meters, however due to the combination of a “red alert” tide and SLA of 0.1 meters, the flooding was greatly enhanced (Stephens, 2015). Water levels reaching the MHWPS elevation have increased by a factor of 3 to 4 from 1900 to 2010 at Auckland, Lyttleton, Dunedin and Wellington due to SLR. This has basically doubled the amount of, “red alert” days over the past century. A quadratic increase in “nuisance flooding” elevations have also been noted by Sweet et al., (2014) in the United States which also highlights the global significance of coastal inundation.

2.8 Return Periods

Return periods are used to assess storm surge hazards. Two main statistical methods are used to determine the likelihood of extreme events such as coastal flooding/inundation (Stephens, 2015). They include the average recurrence interval (ARI), and the exceedance probability (P) for a specified time period (T). The ARI is the average period between extreme events (long term), compared to P which calculates the probability of at least one extreme event during the time period T (Hunter 2012). Many statistical methods use annual exceedance probabilities (AEP), where T=1. For an ARI≥10 years, then the AEP=1/ARI (Stephens, 2015). Extreme sea levels are also calculated using exceedance probabilities for events over a specified level (Hunter, 2012). It has been argued that for risk assessment, an estimate of the number of exceedances (N) over a specified period, is more useful compared to the probability of one or more events occurring (P) (Hunter, 2012). This gives equation 1.2, shown below:

$$N=T/ARI \tag{1.2}$$

Where N=number of exceedances, T=time period and ARI=average recurrence interval. The extreme and empirical (measured) sea level distributions have been plotted for the Port of Auckland (Figure 2-1). This shows the AEP for present day on the lower curve, with the upper AEP curves simulating SLR of 0.3, 0.5 and 1.0 meter. These are primarily based on the 0.01 AEP which has been adopted as a design for SLR coastal planning (Stephens and Bell, 2015), as a level expected to occur only rarely during the combination of larger high tides and storm surges.

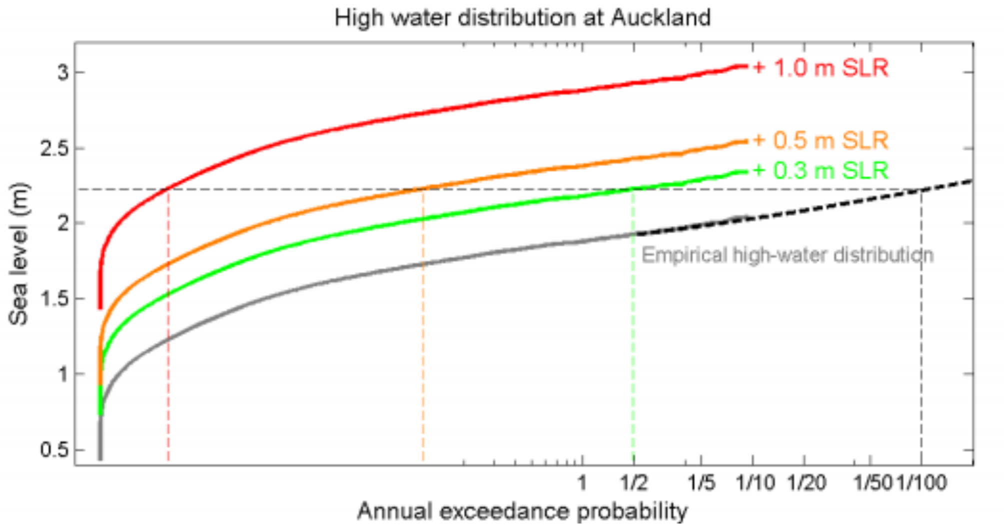

Figure 2-1 High-water distribution at Auckland plotted in terms of annual exceedance probability. Sea levels are specified relative to MSL = 0 (i.e., not relative to the local vertical datum). AEP ≈ 1/ARI for AEP ≤ 1/10. The empirical curves have been truncated at AEP = 1/10 (ARI = 10 years). The lower curve corresponds to present-day sea level, while the upper curves have been raised to simulate sea-level rises of 0.3, 0.5 and 1.0 m. The bold black dashed line marks the extreme sea-level distribution. The horizontal dashed line shows the present-day AEP = 0.01 (or 1%) extreme sea level. The vertical dashed lines show the expected change in the annual exceedance probability of the 0.01 AEP sea level (at present-day MSL) for SLR of 0.3, 0.5 and 1.0 m (Stephens & Bell, 2015).

These exceedance probabilities were also calculated by the number of exceedances in one year, based on the equation from Hunter (2012). From this, you can see that the present day 0.01 AEP is not expected to occur once every year (only 0.01 exceedance in a year). This level of exceedance will be expected approximately once every two years for the 0.3 m SLR, with 10 exceedances for the 0.5 m SLR, and nearly 300 times for the 1.0 m SLR. This shows how extreme sea-levels experienced at present day will be much more frequent in the future. Along with the increased frequency, the overall amplitude of storm tides are expected to increase with SLR, which will result in greater levels of coastal inundation.

The application of AEP is reasonably common in the identification of hazard elevations. de Lange and Gibb (2000b) studied the suitability of using the AEP to quantify extreme water levels at the coast. They highlight that this method assumes extreme events have a random distribution spatially and temporally, and also that the nature of these events do not change with time. Storm surge magnitude and frequency in Tauranga Harbour were shown to vary depending on seasonal changes, ENSO and the IPO between the period 1960 to 1998 (de Lange & Gibb, 2000). This indicates the first assumption is likely invalid. Global SLR means the second assumption is also invalid. AEP are still applied widely as an appropriate tool for hazard analysis such as extreme sea-levels at the coast, with their validity being highest when temporal variability is accounted for (de Lange & Gibb, 2000b).

Extreme sea-levels were calculated for Wellington, Lyttelton and Dunedin from a generalised extreme value (GEV) distribution, fit to annual maxima (AM). This method is the simplest extreme value technique to apply but is only useful for long term data (i.e. >50 years) (Coles, 2001). As expected, the GEV method was found to have similar results to the ones obtained from the MCJP method at Auckland for long term records (Stephens, 2015). The advantages and disadvantages of some commonly applied extreme value (sea level) techniques have been summarized in Figure 2-2. The main difference between the methods are their simplicity and the uncertainty of the results they produce. The choice of extreme value analysis can depend on the quality of the data with respect to the length and sampling frequency of the time series (Bell & Stephens, n.d.). The analysis is sensitive to outliers, and therefore rigorous quality analysis is required. This maximizes the accuracy of extrapolated sea-levels following the removal of erroneous data, spikes, gauge shifts and timing errors. Instrument jamming or fouling of sea-level gauges can also result in periods of missing data.

	Advantages	Disadvantages
Direct methods	**GEV fitted to annual maxima**	
	▪ Simple to apply (no thresholds) with easily-obtained software. ▪ Simple data treatment and post-processing (Annual Maxima easily obtained and quality checked). ▪ Annual Maxima records sometimes extend beyond the modern continuous digital records.	▪ Inefficient use of data (wastage). About 40-years of Annual Maxima required for 100-year ARI estimate. ▪ Long sea-level record required (large uncertainty for short records). In some locations this is partially compensated by Annual Maxima records that extend beyond modern digital records. ▪ Sensitive to large outliers in the data.
	GPD fitted to peaks-over-threshold	
	▪ Most efficient data use of the direct methods (highest confidence, lowest uncertainty). ▪ Commonly applied with easily-obtained software.	▪ Requires subjective choice of threshold – user experience, or trial and error. ▪ At least 10-years of data required for a 50 to 100-year ARI estimate. ▪ Use of more data requires more stringent data quality check.
Indirect methods	**Monte Carlo Joint Probability (MCJP)**	
	▪ Most efficient use of data. ▪ Suitable for short records (< 5-years). ▪ Higher confidence (lower uncertainty). ▪ Stable in the presence of large outlying events.	▪ Sensitive to data errors, requires stringent data quality assurance. ▪ Complex and time-consuming to apply – requires high level of user experience relative to direct methods. ▪ Less commonly applied and available software. ▪ Assumes tide and storm surge are independent, which may not be true in estuaries

Figure 2-2 Summary of extreme value techniques used for estimating the probabilities of extreme still water levels. GEV=generalised extreme value model; GPD=generalised Pareto distribution (Stephens & Bell, 2015).

2.9 Vegetation

Aquatic vegetation can reduce the impact of storm surge, waves, currents and tsunamis on certain coastlines, and can also trap sediment (Liénard et al., 2016). Coastal stability can therefore be increased through this mechanism. Due to SLR and increasing coastal development, there has been a research focus toward the ability of aquatic vegetation in reducing coastal inundation and erosion. The dissipation of energy at these locations is based on the density and morphology of the vegetation, and these conditions must be measured and used in local scale studies to quantify their effect (Liénard et al., 2016). In Tauranga Harbour, vegetation such as mangroves could provide natural greenbelts which if implemented appropriately, have the ability to mitigate coastal hazards.

Chapter Three

Sea-level Data and Extreme Value Analysis

3.1 Sea level components

Extreme sea-levels at the coast result from a combination of meteorological and astronomical processes (Figure 3-1). Coastal inundation of low-lying land can result from the combination of these components. There is uncertainty regarding the components of sea-level included in Gibb's (1997) historical observations of extreme sea-levels. This is because modern tide gauges are designed to reduce the impact of waves, and only measure the still sea-level. Due to short sea-level records, many efforts to reconstruct historical measurements of extreme sea-levels have used surveys of flotsam lines which includes the added elevation from wave run-up. In general, the sea-level components that should be considered in any extreme sea-level study are the:

- Mean sea-level (MSL): The averaged or mean sea-level with respect to the local vertical datum (MVD-53 used for this research in Tauranga Harbour), over a long period of time, generally several years.

- Mean sea-level anomaly (MSLA): The variability in the non-tidal sea-level over periods ranging from months to decades, which is generally the result of changing climate.

- Wave setup and run-up: Setup is the temporary increased sea-level which results from wave action at the coast. Run-up is the added elevation experienced when the wave moves upward ('uprush') on the beach face or land boundary.

- Wave overtopping: When wave run-up exceeds the elevation of the beach berm, dune, seawall or land boundary in which case water flows over and 'overtops'.

- Storm surge: Temporary changes to the sea-level induced by winds and barometric pressure associated with weather systems.

- Sea-level rise (SLR): Long term changes to sea-level caused by changes to the climate.

- Vertical land movement (VLM): If the land is being up-lifted by tectonic activity at a faster rate than sea-level is rising, then the sea-level may appear to be falling. In comparison, is the land is subsiding, SLR is enhanced and should be managed accordingly.

- Tsunami: Resulting from earthquakes, landslides and volcanoes.

- Storm-tide: This is the combination of the major sea-level components excluding wave setup and run-up. This includes MSL, MSLA, high tide and storm surge (Figure 3-1). This level does not include effects from waves, and is therefore a suitable measure of the still-water level.

- Total water level (TWL): The combination of all components, including wave effects. This includes MSL, MSLA, high tide, storm surge, wave setup and run-up. The report by Gibb (1997) used *storm surge* when referring to TWL.

There are multiple ways storm surge can be calculated and/or defined. The difference between the observed TWL and the nearest predicted high tide is termed skew surge. The name is given because the TWL may occur after or before the predicted high tide. Gibb (1997) along with de Lange & Gibb (2000) measured storm surge using this method. The term storm-tide was used by Gibb (1997) when referring to the skew-surge. The difference between the observed TWL and non-tidal residual (NTR), which is the hourly predicted tide. The study by Goring et al., (1997) used the revised joint-probability method (RJPM) to extract storm surge using this method.

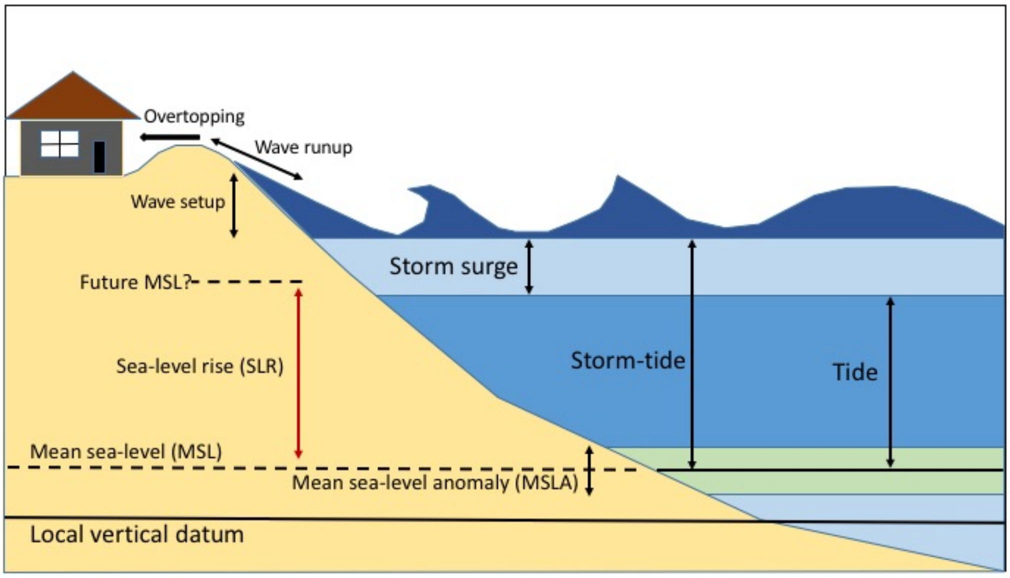

Figure 3-1 Components contributing to sea-level variability (adapted from Stephens, 2017).

It is important to consider the different methods for obtaining extreme sea-level data. Tide gauges provide accurate measurements with confidence levels of the still-water level. Post storm surveys of flotsam lines usually incorporate added elevation from wave run-up, unless two separate lines can be identified (representing the still water level and wave run-up). Eye witness accounts and oral histories can add extra uncertainty as to the exact location and extent of the seas reach, even with photographic evidence. The study by Gibb (1997) and other studies using flotsam lines, would have incorporated the added elevation from wave effects.

3.2 Sea-level Data and High Water Elevations

Sea-level data was obtained from four gauges inside Tauranga Harbour (Tug Berth, Hairini, Oruamatua and Omokoroa) and one on the open coast (Moturiki Island) (Figure 3-2). The time series data are described in Table 3-1.

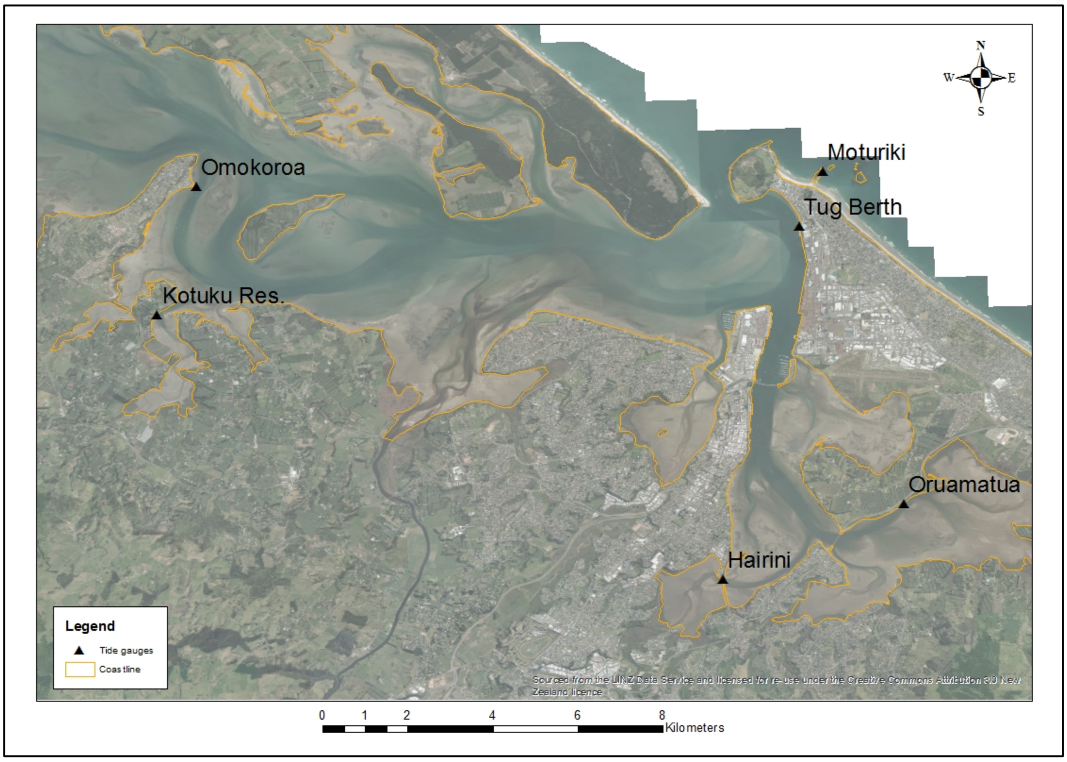

Figure 3-2 Map showing the location of sea-level gauges used in the study.

The Moturiki gauge is the only gauge located on the open coast, and is maintained by the National Institute of Weather and Atmospheric Research (NIWA). The Bay of Plenty Regional Council (BOPRC) operates and maintains the Hairini, Oruamatua and Omokoroa gauges, along with the previously-operated gauge at Kotuku Reserve. The new gauge at Omokoroa is located at the wharf and has been in operation since 2014. Data from this gauge have been combined with data from the Kotuku Reserve gauge, which operated from 2000 to 2014, located in close proximity at Plummers Point. This follows methods used by Stephens (2017) in his report on storm tides in Tauranga Harbour, which also used data from the same gauges.

The Port of Tauranga supplied data for the Tug Berth gauge from 2002 to 2016. This was supplied to NIWA for the Tauranga Storm Tide Report in 2017, and was added to their Tug Berth data archive from 1989 to 2016. NIWA then resupplied quality analysed data for all gauges. LINZ provided data for Tug Berth from November 2016 to the end of January 2018, which was quality analyzed as part of this thesis before being added to previous data. The BOPRC supplied data from

Hairini, Oruamatua and Omokoroa from January 2017 until the end of January 2018, which was also quality analyzed before being added to previous data.

Table 3-1 Sea-level time series data.

Gauge name	Location	Record start	Record finish	Sampling frequency
Moturiki	Moturiki Island	1 Jun 1974	28 Feb 2017	Hourly
Tug Berth/Salisbury Wharf	Mount Maunganui	1 Jun 1989	30 Jan 2018	Hourly
Hairini	Hairini Bridge	5 Apr 2002	30 Jan 2018	Hourly
Oruamatua	Oruamatua	10 Jan 2001	30 Jan 2018	Hourly
Kotuku	Plummers Point	24 Nov 2000	18 Aug 2014	Hourly
Omokoroa	Omokoroa wharf	18 Aug 2014	30 Jan 2018	Hourly

Storm surge time series were plotted for all the sea-level gauges (Figure 3-3). The longest sea-level record used in the study is from Moturiki, operating from 1974. The Tug Berth time series starts in 1989. The Kotuku gauge started operating late in 2000, and was joined to data from Omokoroa which started operating nearby in 2014. The Oruamatua time series starts from 2001, and Hairini starts from 2002.

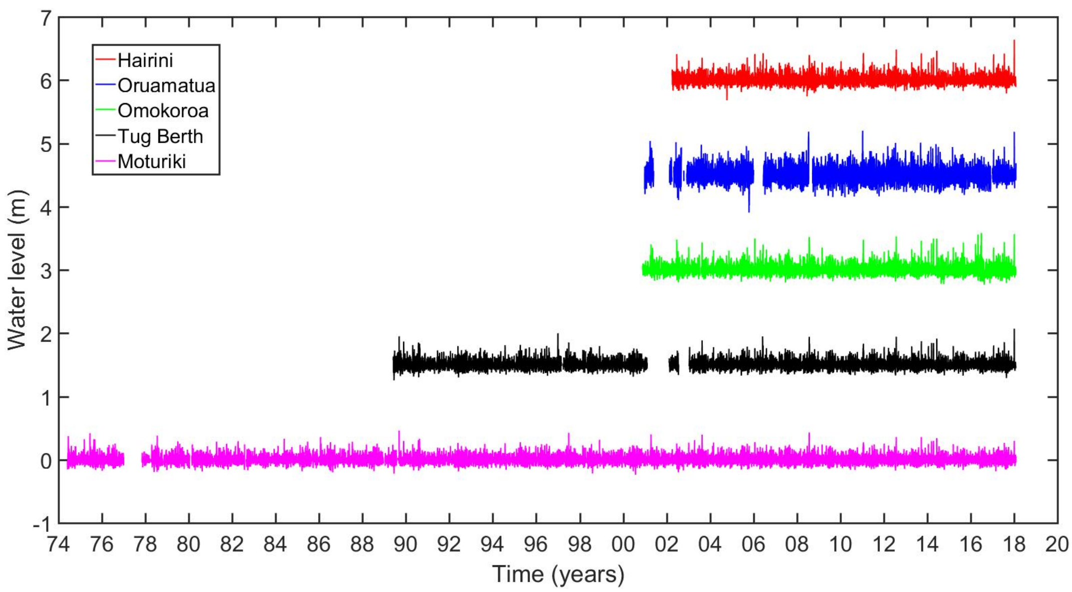

Figure 3-3 Storm surge time series for the sea-level gauges.

3.2.1 Vertical Datum

The following datum's are defined due to their relevance to this research.

LVD: The Local Vertical Datum (LVD) in the BOP region is Moturiki Vertical Datum 1953 (MVD-53). LVD are located around New Zealand. Due to sea-level rise, the present day MSL is usually several cm higher and therefore confusing to refer to the LVD as a MSL datum.

Gauge zero: The zero datum of the sea-level gauge. Gauge zero on the long term permanent sea-level recorder at Moturiki is 1.487 m below MVD-53. Gauge zero for the Tauranga (Sulphur Point) and Mount Maunganui (Tug Berth) gauges is 0.963 m below MVD-53 (de Lange & Gibb, 2000; Stephens, 2017).

MSL: Mean sea-level (MSL) averaged over periods of at least 1 month, but usually up to several years. MSL changes over temporal scales due to long period variations in sea level. This is different from sea-level anomaly (SLA) which is the average MSL over a specified time. Effects from El Niño-Southern Oscillation (ENSO), long-term sea-level change and seasonal variation are included in SLA. MSL is typically expressed relative to a fixed vertical datum (i.e. LVD or gauge zero).

3.2.2 High-tide elevations and tidal constituents

Tidal constituents and mean-high water springs (MHWS) elevations are summarized for each sea-level gauge in Table 3-2. All tidal constituents for each gauge and their corresponding time series are listed in Appendix 1. MHWS7 refers to the high tide elevation of the highest 7% tides. Mean high water perigean springs (MHWPS) equates to the total of the M2, N2 and S2 constituents. Mean high water (MHW) is the average of all high tides. The M2 tidal constituent is dominant around New Zealand.

Table 3-2 Tidal constituents and mean-high water springs elevations.

Sea-level gauge	M2	N2	S2	MHWS7	MHWPS	MHW
Moturiki	0.73	0.16	0.10	0.96	0.98	0.75
Tug Berth	0.70	0.14	0.09	0.90	0.93	0.70
Oruamatua	0.73	0.14	0.09	0.96	0.95	0.75
Hairini	0.71	0.14	0.08	0.94	0.93	0.73
Omokoroa	0.72	0.15	0.08	0.91	0.94	0.72

3.3 Quality Analysis of Sea-level Data

Data that had not been quality analysed included the Omokoroa gauge for the period August 2014 to the end of January 2018. Recent Tug Berth sea-level data was quality analysed for the period November 2016 to the end of January 2018. Both the Hairini and Oruamatua tide gauges were quality analysed for the period January 2017 to the end of January 2018.

The procedure for quality control of the data was undertaken as follows:

1. A copy of the raw data files were made and saved for quality analysis.
2. The time series was decimated into equal time steps. Due to gauge upgrades, sampling frequency increased to every minute, and therefore needed to be changed to hourly data to maintain a consistent time step. Hourly data was sufficient for this research in resolving tides, storm surges and mean sea level anomaly (Stephens, 2017).
3. De-spiking of data was carried out on sea-levels which were considered impossible. Deletion of these values is preferable for hourly data, and therefore they were given NaN (not a number) values in MatLab.
4. Unitide software was used to carry out tidal predictions (Foreman et al., 2009). This software is capable of ignoring missing values.
5. The non-tidal residual (NTR) was calculated by subtracting the predicted tide from the measured tide (Goring, 2006; Stephens, 2017).
6. Mean sea level anomaly (MSLA) was calculated by running a monthly mean, and was then subtracted from the NTR to obtain storm surge.
7. An example of the completed sea-level components (measured tide, predicted tide, storm surge and MSLA) are plotted for Tug Berth in Figure 3-4.

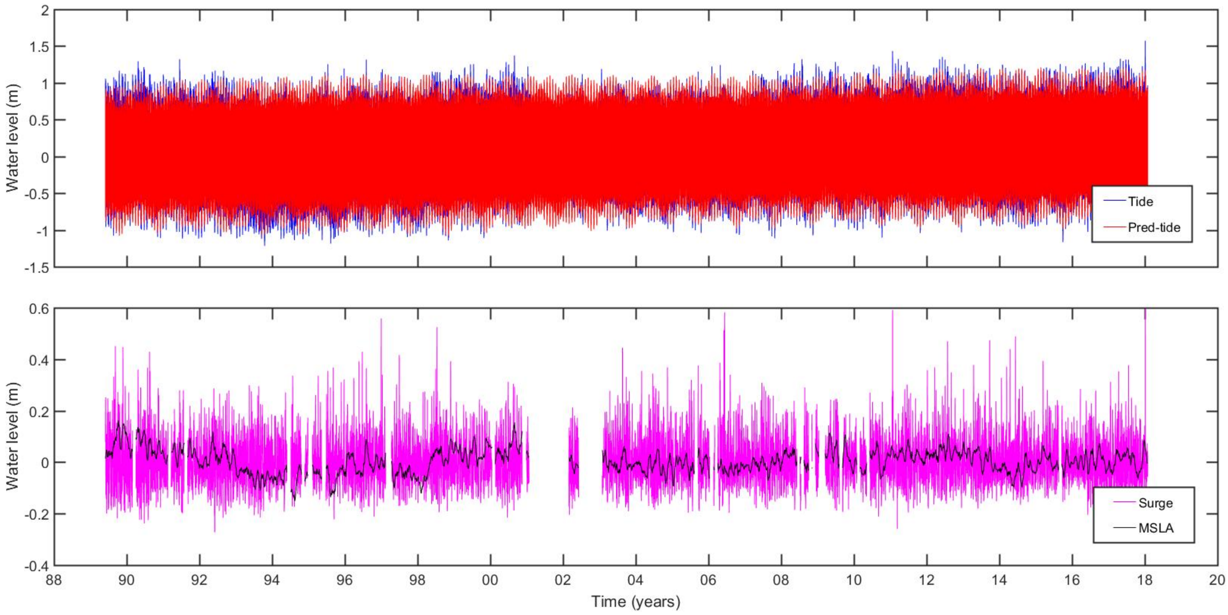

Figure 3-4 Tug Berth time series, showing the recorded tide, predicted tide, storm surge and mean sea-level anomaly.

3.4 Extreme Value Analysis

Extreme value theory uses statistical methods to quantify the nature of extreme events (Coles, 2001). In this research, the extreme values of storm surges were calculated, with the aim of using the statistical properties to predict their likelihood of occurrence into the future. This is necessary for storm surges as, unlike tides, they cannot be forecasted accurately into the future, and have not been studied extensively in New Zealand. Storm surge data is generally restricted to short sea-level records, along with modelled hindcasts. Statistical analysis of extreme sea levels can be carried out using either, (1) direct, or (2) indirect methods.

1. Direct methods involve fitting a model to independent maxima extracted from the time series. There are two different models which can be fitted. The generalised extreme-value model (GEV) is fitted to maxima from specified blocks (usually annual), known as the annual maxima (AM) method. This is the simplest to apply, however uses less of the data (i.e. only using one maxima per year). The generalised Pareto distribution (GPD) is commonly fitted to independent peaks found above a selected threshold, known as the peaks-over threshold (POT) method.

2. Indirect methods, such as joint-probability methods, involves splitting the sea-level into both tidal and non-tidal constituents. These are modelled separately and then combined, and so the output allows a larger range of more extreme values than may have occurred in the data records used for the calculations.

The fit of these extreme value models can be checked by plotting them against the measured maxima, along with their associated confidence intervals. Extreme values are plotted based on their Gringorten positions, assuming they follow a double exponential (Gumbel) distribution (Gringorten, 1963). This is the plotting positions for ranked exceedances, shown in equation (1.2):

$$p_i = \frac{i - 0.44}{n + 0.12} \tag{1.2}$$

Where *Pi*= annual exceedance probability (AEP) of the *ith* point, *i*=the *ith* ranked from largest to smallest, and *n*=sample size of POT. Two different extreme value theory methods were applied to sea-level records here. This included AM and POT, with results being used from the POT method. POT is generally preferred over AM as it uses more of the available data, instead of only one maximum per year.

3.5 Peaks Over Threshold Analysis

The POT method was applied to sea level data from tide gauges in Tauranga Harbour using purpose built MatLab software and the built in fitting routines. To calculate POT, a threshold (u) was set (see Section 3.5.1.) and all observations exceeding this value are identified. When peaks were found that were closely spaced in time, a de-clustering method was used to ensure each peak value is identified as an independent event (storm surge). A distance value of two days (48 hours) was used to separate surge events (i.e. multiple peaks occurring within 48 hours of each other are classified by the same cluster/storm surge event) (Figure 3-5).

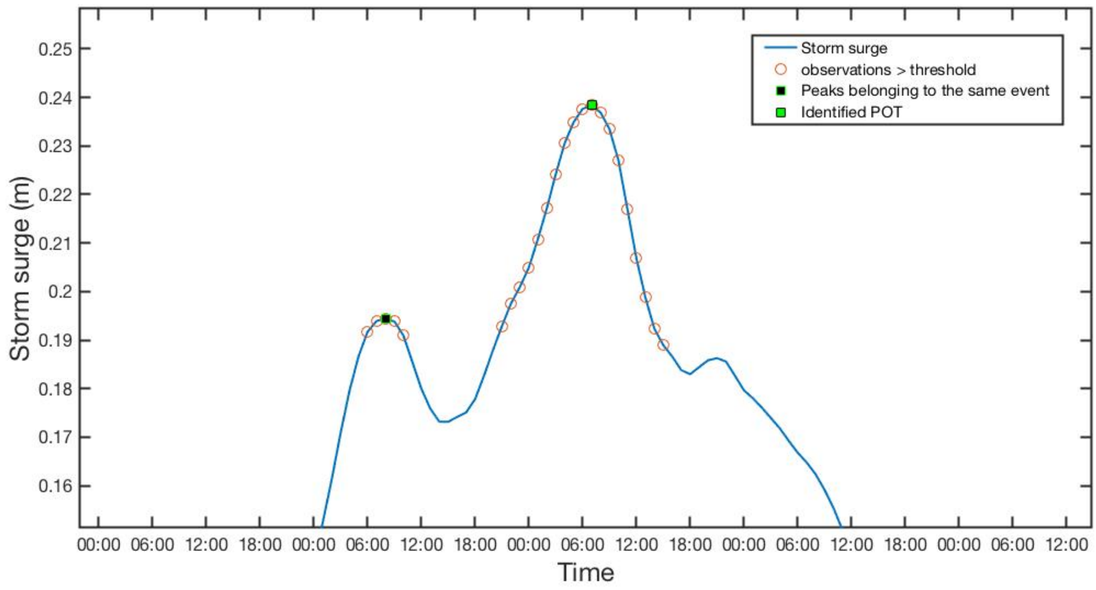

Figure 3-5 Plot showing the method used to obtain peak values (POT) for storm surge events above the threshold (u).

After POT have been identified for independent events, the GPD was fitted and their return periods calculated by determining their rate of occurrence (Caires, 2011). This method predicts the probability of events irrespective of the year within which it occurs, unlike the AM (Dunne & Leopold, 1978).

3.5.1 Threshold Selection

The u was set at the 99th percentile for storm surge at each sea-level gauge. This was calculated using the mean excess function along with the additional technique of determining satisfactory number of exceedances after fitting a range of different thresholds. When dealing with long time series data from multiple different locations, a common method to find the threshold has been to use percentiles (Godoi et al., 2017). The choice of threshold for the POT method is a balance between variance and bias. There are a variety of techniques which can be used to select the threshold. Coles (2001) recommends two (i) calculating the mean excess function for exceedances and plotting these against u, and/or (ii) fitting the GPD to POT for a range of different thresholds. Two important parameters for selecting an appropriate threshold value are the scale (σ_u), and shape (ξ) which are fitted by the GPD software. The distribution function for the GPD is given below in equation 1.3.

$$F_u(y) = \begin{cases} 1 - \left(1 + \xi \dfrac{y}{\sigma_u}\right)^{-1/\xi}, \text{ for } \xi \neq 0 \\ 1 - \exp\left(-\dfrac{y}{\sigma_u}\right), \quad \text{for } \xi = 0, \end{cases}$$

(1.3)

Where $0 < y < \infty$, $\sigma_u > 0$ and $-\infty < \xi < \infty$. "When the $\xi = 0$, the GPD is said to have a type 1 tail and amounts to the exponential distribution with mean σ_u ; when $\xi > 0$ it has a type 11 tail and it is the Pareto distribution; and when $\xi < 0$ it has a type 111 tail and is a special case of the beta distribution" (Caires, 2011, p.4). The maximum likelihood method was used to estimate these parameters of the GPD (along with corresponding confidence levels). This was carried out in MatLab using a function called, 'gpfit.m'. The mean excess function is commonly used when applying POT, to set an appropriate threshold. The empirical mean excess function is given in equation 1.4 and was calculated for a range of different threshold values, ranging from the 90th to the 99th percentile (Figure 3-6).

$$E^{GPD}(u) = (\sigma_u + \xi u)/(1-\xi) \qquad (1.4)$$

Where E^{GPD}=mean excess, u=threshold, σ_u=shape parameter of GPD and ξ=scale parameter of GPD. With regard to the GPD, it is a linear function which only becomes linear (approximately) at higher values, and is used as an indicator for setting the threshold level. The mean excess plots for all five gauges show similar patterns, with values becoming linear at approximately the 98th percentile.

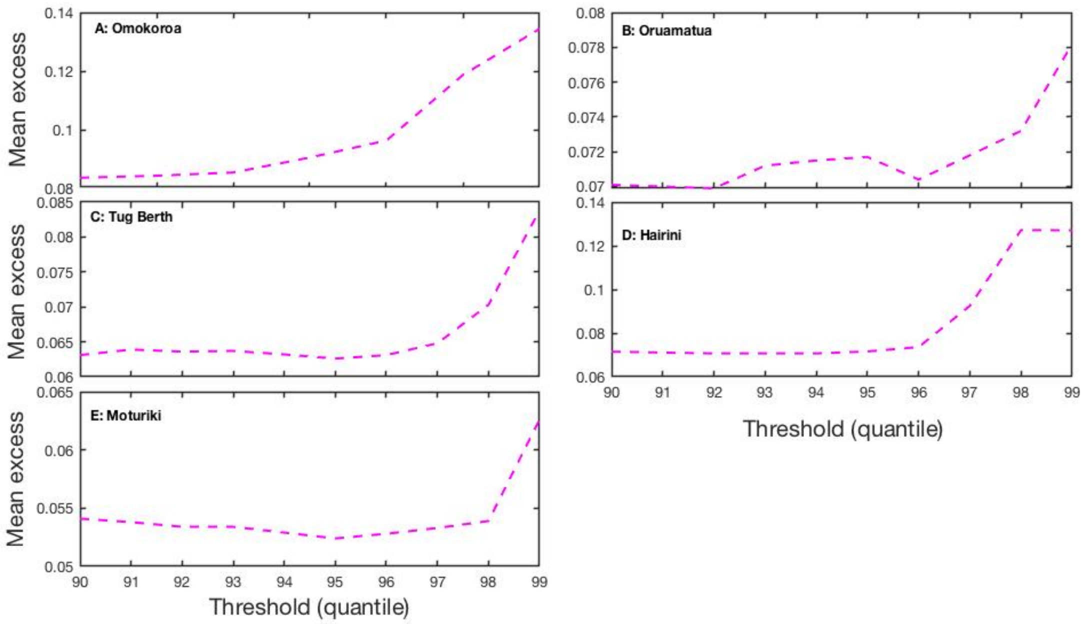

Figure 3-6 Sample mean excess plot for storm surge thresholds, ranging from the 90th to 99th quantile.

The choice of threshold for the POT method is subjective in that the user decides where the fit becomes linear. Bias can occur when the threshold is set too low. High variance can occur when the threshold is set too high, which is because too few exceedances are considered in the model. For the POT method, a maximum of four storm tides/surges per year has been suggested as suitable to remove bias (Van den Brink et al., 2005). For this research, the 99th percentile produced an appropriate number of exceedances per year (and resulted in the mean excess plots becoming linear), and therefore was used as the threshold value for each sea-level gauge in this study.

3.6 Results: Comparison of Extreme Storm Surge levels

Extreme sea-levels from storm surges inside Tauranga Harbour were calculated using the POT method (see section 3.5). Extreme storm surges were calculated at four tide gauges inside Tauranga Harbour (Tug Berth, Hairini, Omokoroa and Oruamatua), and one on the open coast (Moturiki). These extreme values along with their fitted GPD are plotted in Figure 3-7 and 3-8.

Extreme storm surges were found to be higher at sea-level gauges inside Tauranga Harbour, compared to on the open coast at Moturiki. The highest storm surges occur at Omokoroa, followed by Hairini (Figure 3-7). Oruamatua and Tug Berth have similar sized extreme storm surges, however are slightly larger at Oruamatua. The lowest extreme storm surges occur at Moturiki, on the open coast.

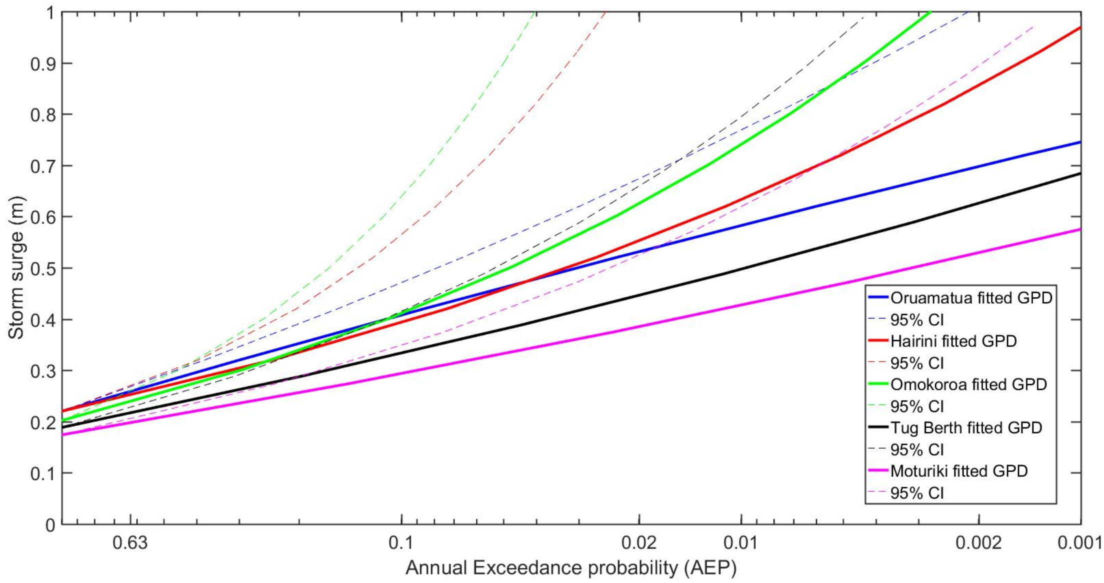

Figure 3-7 GPD fitted to sea-level gauges POT storm surges, with only the upper 95% confidence interval.

As predicted the results from the fitted GPD have large uncertainty, shown by the wide confidence intervals (95%) (Figure 3-8). Moturiki has the highest confidence, because a longer sea-level record was used. In comparison, the largest uncertainty are from the Council operated gauges which have shorter records (operating from the early 2000s).

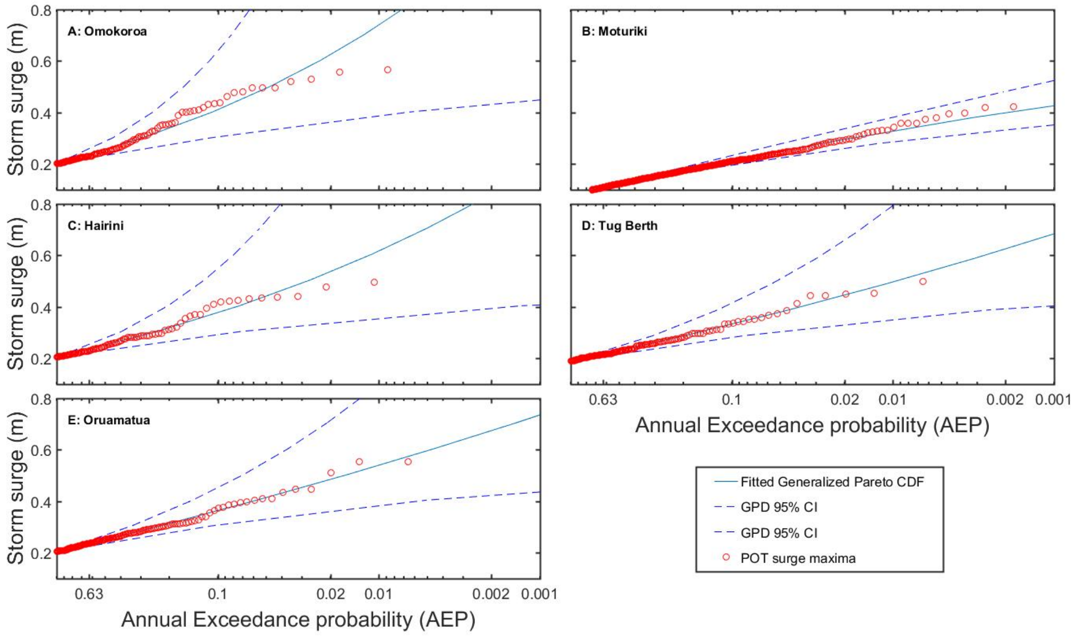

Figure 3-8 Generalized Pareto Distribution (GPD) fitted to peaks over threshold (POT), for the sea-level gauges.

Table 3-3 summarizes the estimated return periods (AEP/ARI) based on the storm surge extreme value analysis. In order from highest to lowest extreme storm surge values, the corresponding sea-level gauges are Omokoroa, Hairini, Oruamatua, Tug Berth and Moturiki. The 0.01% AEP (100 year ARI) ranges from 0.34 m at Moturiki, up to 0.75 m at Omokoroa.

Table 3-3 Annual exceedance probability (AEP) and average recurrence interval (ARI) for the fitted extreme storm surge distributions.

AEP	0.1	0.02	0.01	0.005	0.002
ARI	10	50	100	200	500
Moturiki	0.22	0.30	0.34	0.37	0.40
Tug Berth	0.34	0.45	0.50	0.56	0.63
Oruamatua	0.41	0.54	0.59	0.64	0.70
Hairini	0.40	0.56	0.64	0.73	0.86
Omokoroa	0.42	0.63	0.75	0.87	1.08

On the 5th January 2018 the largest storm surge was measured in regard to both the Hairini and Tug Berth sea-level records, with values of 0.64 m and 0.57 m respectively. With regard to the extreme value analysis this corresponds to estimated ARI of 100 years at Hairini, and 200 years at Tug Berth. This event was the second largest storm surge on record at Omokoroa and Oruamatua, with values of 0.57 m and 0.56 m respectively. This corresponds approximately to the estimated ARI of 20 years for Omokoroa, and 70 years for Oruamatua. The Omokoroa sensor failed during the peak of the event and would have likely been higher, which would produce a longer return period than what is estimated here. This event was the 25th largest for the Moturiki sea-level record with a value of 0.29 m which corresponds approximately to the estimated ARI of 50 years. This shows that individual storm surge events can have different estimated return periods due to spatial variations in storm surges, along with differences in the periods (length) of the time series data.

3.6.1 Return Period and Gauge Distance from the Southern Entrance

One of the research aims was to investigate how storm surges change in different parts of Tauranga Harbour. Sea-levels from storm surges are shown to be variable based on location. The 0.1% AEP (10 year ARI) for each sea-level gauge was plotted against their distance from the southern entrance of Tauranga Harbour (Figure 3-9). The key finding was that the 0.1% AEP storm surge is higher at sea-level gauges located further from the southern entrance. The result is statistically significant with r^2 value of 0.96, and p value 0.03. The Omokoroa sea-level gauge is located furthest away from the entrance at approximately 11 km, with the largest value of 0.415 m. Oruamatua is located 10.3km from the entrance with the second largest value of 0.41 m. This is followed by Hairini at a distance of 9.7 km with value 0.39 m, and Tug Berth at a distance of 1.86 km with value 0.33 m. Moturiki is located on the open coast (given a value of 0 km from the entrance), with the lowest value of 0.28 m.

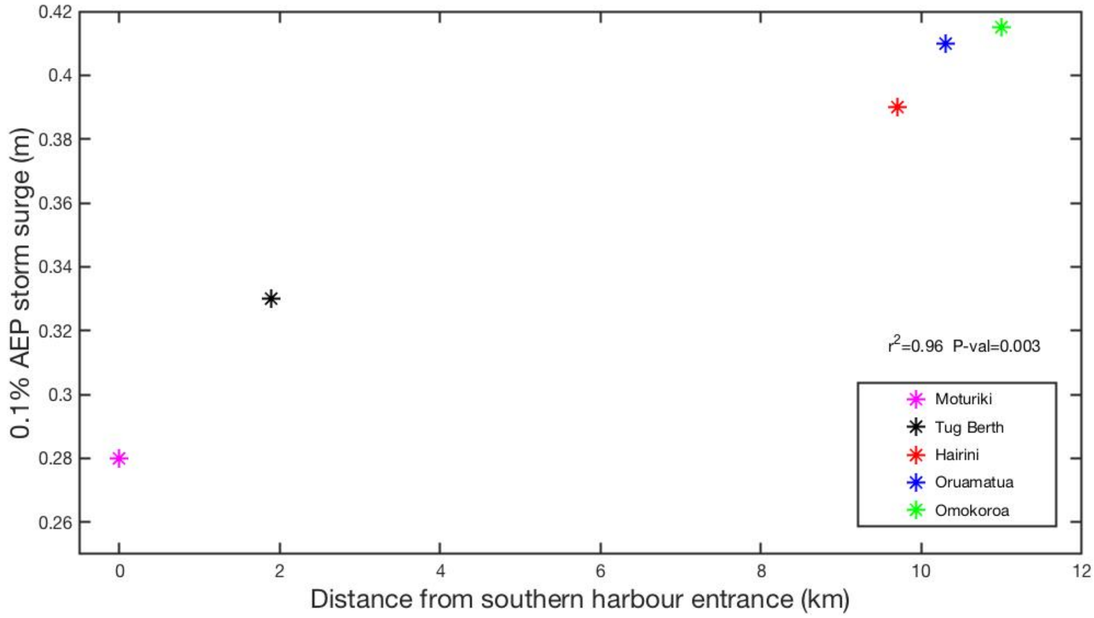

Figure 3-9 Plot of distance (from the southern Harbour entrance), against the 10 year storm surge return period.

The POT method was also applied to the recorded TWL for the sea-level gauges (Figure 3-10). Oruamatua experiences the highest extreme sea-levels, followed by Hairini. Omokoroa and Moturiki have the next highest levels, with the lowest measured extreme sea-levels at Tug Berth.

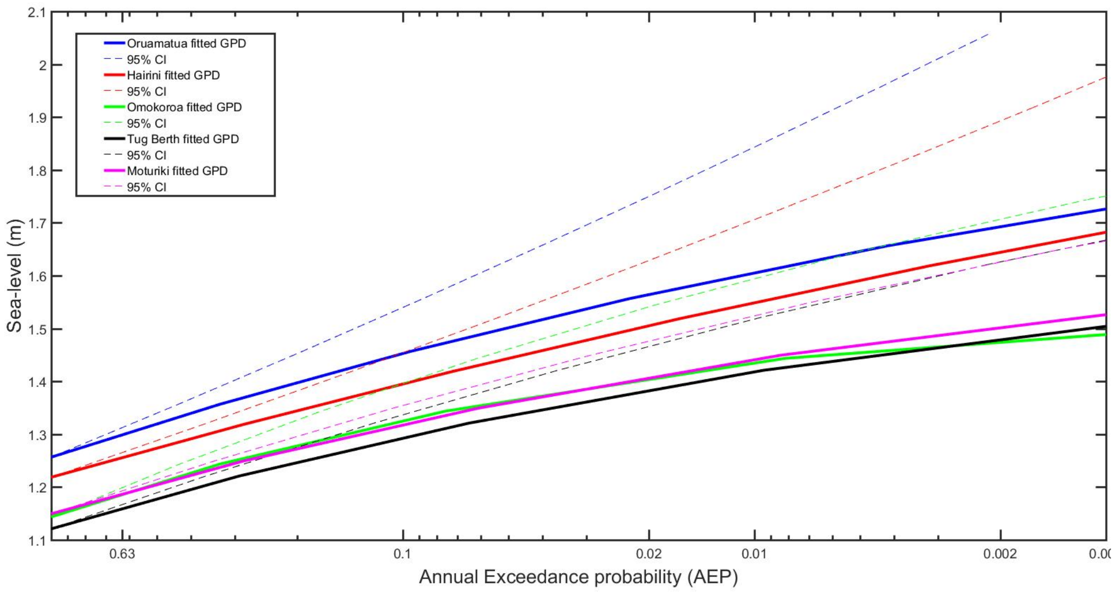

Figure 3-10 GPD fitted to POT for total measured sea-level at the sea-level gauges (including the upper 95% confidence interval).

The extreme value analysis results for TWL at the sea-level gauges are summarized in Table 3-4.

Table 3-4 Annual exceedance probability (AEP) and average recurrence interval (ARI) for the fitted extreme TWL distributions.

AEP ARI	0.1 10	0.02 50	0.01 100	0.005 200	0.002 500
Moturiki	1.32	1.41	1.45	1.48	1.50
Tug Berth	1.29	1.38	1.42	1.45	1.48
Oruamatua	1.46	1.56	1.61	1.65	1.70
Hairini	1.39	1.51	1.55	1.59	1.65
Omokoroa	1.33	1.41	1.44	1.46	1.48

3.6.2 Comparison with WASP model and hindcast

The National Institute of Weather and Atmospheric Research (NIWA) produced a waves and storm surge projection (WASP) model hindcast around New Zealand for a 45 year period from 1958 to 2002 (NIWA, 2010). The output data was produced at regular intervals around the entire coastline along the 50 m depth contour. The main aim of WASP was to produce a hindcast which can be used nationally. This provides information to all regions, increasing our ability to adapt to pressures from climate change. This applies not only to sea level rise, but variations in waves and storm surges.

The WASP output has been supplied by NIWA for this research, and was compared with observed sea level data from the gauge at Moturiki. Another storm surge model hindcast was provided by University of Cantabria (UoC) which is part of the natural Hazards Platform project on weather related hazards. The POT method was applied to storm surge from Moturiki, and both the WASP and UoC hidcasts, with GPD fitted to extreme storm surge levels (Figure 3-11 and 3-12). Extreme storm surges at Moturiki were compared against the models based on their overlapping time periods from 1974 to 2002.

Extreme storm surge elevations are higher at Moturiki in comparison to both hindcasts (Figure 3-11). WASP has slightly larger storm surges compared to the UoC hindcast, representing the extreme storm surge events slightly better compared to the UoC hindcast. The upper confidence interval associated with WASP is higher.

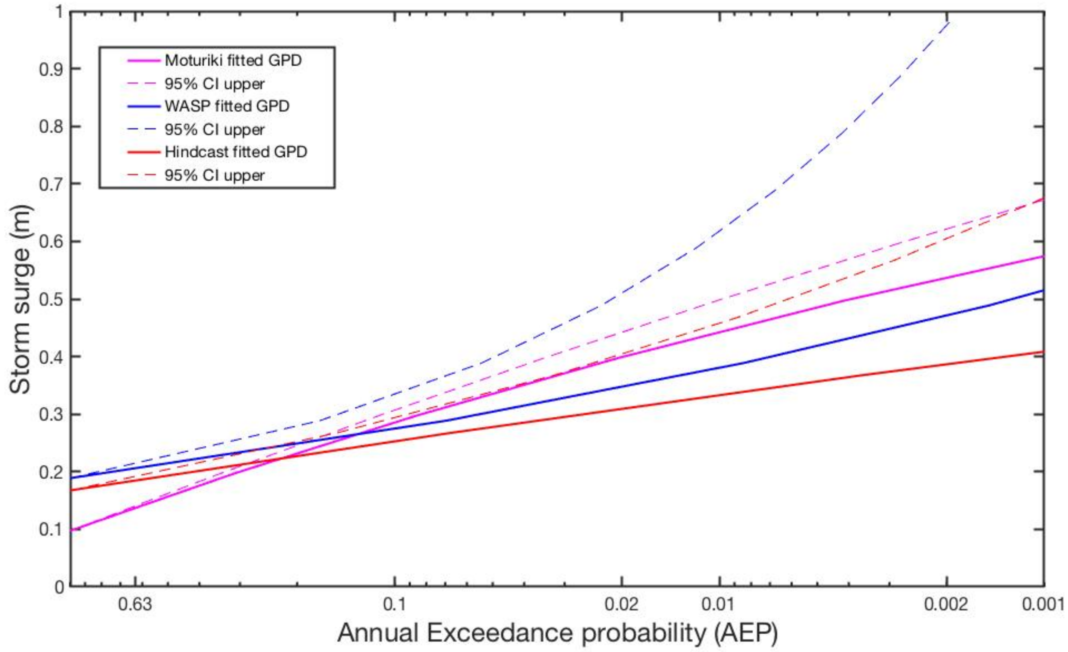

Figure 3-11 GPD fitted to POT for Moturiki, and storm surge model hindcasts from WASP (blue line) and UoC (red line).

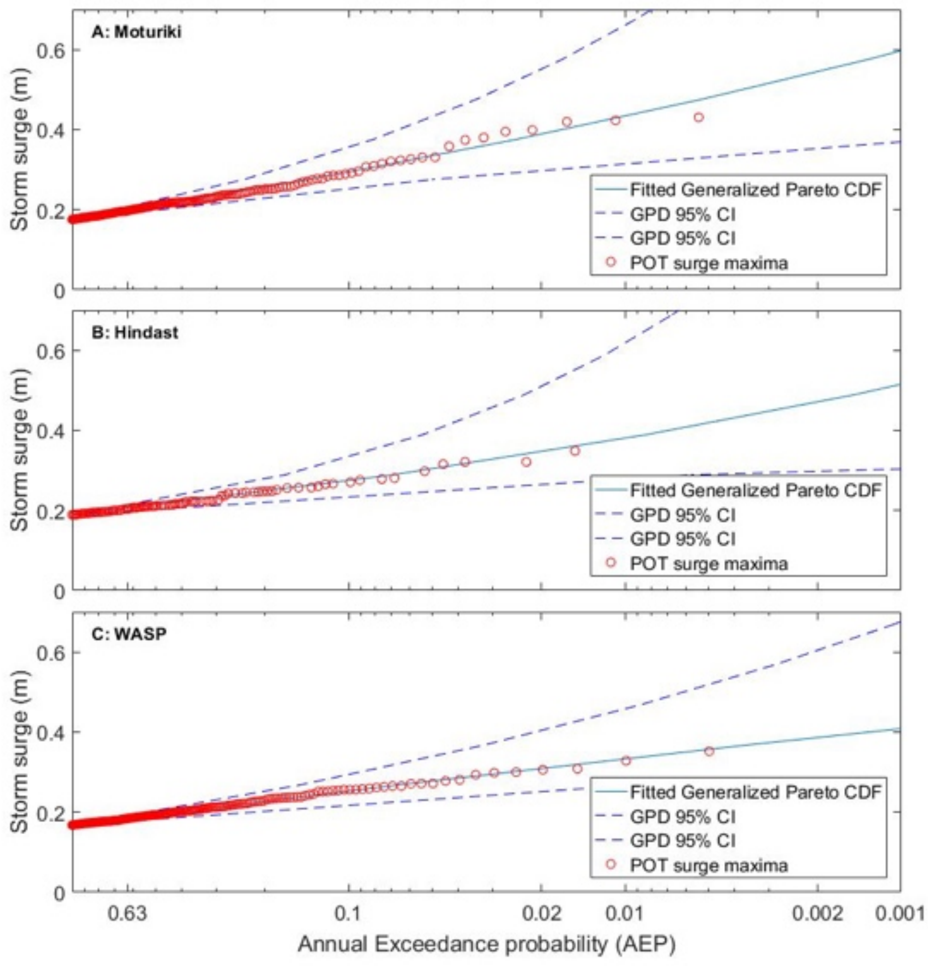

Figure 3-12 Subplot showing the GPD fitted to Moturiki, WASP, and the UoC hindcast.

Both hindcast models generally do well to represent storm surge at Moturiki. The results show that both hindcasts slightly over-predict the height of storm surges at lower extreme sea-levels (approximately <0.1 AEP) and under-predict more extreme storm surges in comparison to Moturiki. This can be observed from observations of storm surges, shown by comparing levels between Moturiki and the UoC hindcast over a short segment of time (Figure 3-13).

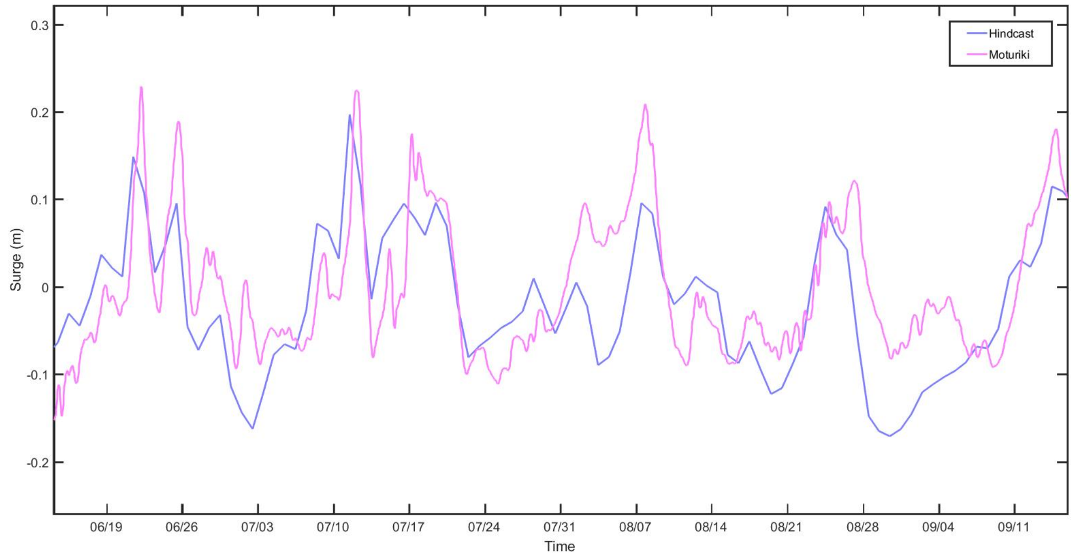

Figure 3-13 Comparison of storm surge at Moturiki and modelled storm surge from UoC hindcast, over a short segment of time.

3.7 Discussion

The results show that extreme storm surges are larger inside Tauranga Harbour compared to Moturiki on the open coast. Surges are largest at Omokoroa, Hairini and Oruamatua, and are lower at Tug Berth and Moturiki. Stephens (2017) also highlights that extreme sea-levels are highest at Omokoroa, but reports Hairini having the lowest levels due to dissipation of the tide and surge into Hairini basin. High extreme sea-levels at Oruamatua are in agreement with Stephens (2017).

Storm surge variation in Tauranga Harbour is not amplification of the surge generated at the entrance but instead locally-generated surge. The Omokoroa Peninsula is located close to the centre of the Harbour and is a known location that experiences high sea-levels due to larger fetches inside Tauranga Harbour from the north to north-west. Omokoroa golf course occupies low lying land on the northern side of the Peninsula. The golf course is known as an area which experiences coastal inundation during extreme sea-level events, and also struggles with drainage where rainfall can enhance inundation, such as the 5th January 2018 event (see Chapter 5). Stephens (2017) suggests large storm surges at Oruamatua are due to reflectance and amplification inside Rangataua Bay, relative to Tauranga.

Stephens (2017) incorporated the large historical sea-levels from Gibb's (1997) survey to calculate extreme sea-levels in Tauranga Harbour. These observed levels would have likely included effects from wave run-up. Stephens (2017) combined two data sets by using the levels from the three historical cyclones to adjust the extreme sea-level distribution. Stephens (2017) refers to these three large events as coming from a different population compared to the more recent sea-level records. The reasons for this are:

1. Because the cyclones that generated them were larger than usual (category 3 and 4).
2. The surveyed sea-level data set from Gibb (1997) likely incorporates added elevation from waves to an unknown degree. Data from the sea-level gauges does not incorporate effects from waves.

The event on the 5th January 2018 produced the largest measured storm surge for both the Tug Berth and Hairini sea-level gauge records used in this study. This event has an estimated return period of between around 20 years at Omokoroa up to 200 years at Tug Berth. For comparison, the three large historical storm surges from 1968, 1954 and 1936 were given estimated return periods of 46, 76 and 214 years (0.021, 0.013 and 0.005 AEP) based on the extreme value analysis by Stephens (2017). Cyclone Gisele in 1968 produced recorded storm surges of 0.76 m and 0.88 m at Mount Maunganui (Salisbury Wharf), and Sulphur Point respectively. The ARI for this event was 46 years, being the smallest of the three historical events. For comparison, the 100 year ARI (0.01% AEP) for this study produced storm surge values of 0.34 m at Moturiki, 0.50 m at Tug Berth, 0.59 m at Oruamatua, 0.64 m at Hairini and 0.75 m at Omokoroa. More information on estimated return periods for storm surge events are discussed in Chapter 4 and 5.

Extreme value techniques generally incorporate large levels of uncertainty in their results, controlled mainly by the quality, length and frequency of time series data used. The GPD fitted to POT in methods used for this study have a larger uncertainty in comparison to joint probability methods, including MCJPM and SSJPM. This is largely because the other methods use more of the available data, and can better overcome difficulties with tide-surge interaction (Batstone et al., 2013). The sea-level records used for this research did not include the three large historical cyclone events, and as expected the extreme sea-level distribution is lower compared to Stephens (2017).

Goring et al., (2010) obtained extreme sea-levels from short time series from Moturiki, using a joint probability method. Their results align with previous work which used the traditional method, fitting the extreme value distribution to AM (direct method) for a 33 year record. The extreme sea-levels calculated using these methods were also smaller in elevation compared to Stephens (2017). The most accurate extreme sea-level analyses are ones that cover a period of at least 18.6 years (one tidal epoch), capturing the full range of tidal elevations (Masselink et al., 2011). In New Zealand this is of greater significance as the tide is the largest component influencing sea-level variability. Sea-level records from Moturiki and Tug Berth are sufficiently long, compared to the more recent Council gauges (Omokoroa, Oruamatua and Hairini) which are just short of covering a tidal epoch.

Both hindcasts represent the general pattern of storm surge at Moturiki, however seem to under predict many extreme storm surge events. This could be due to the modelled hindcasts lack of ability to represent storm surges from tropical cyclones and large storms, however future research it needed. This could involve analysis of whether all under predictions are related to the same type of storm/cyclone.

The role of the tides on the variability in sea-level is significantly large in New Zealand. The largest storm surge on record of 0.85 m was recorded in Tauranga during cyclone Gisele in 1968, however tides can be up to 2 m during spring tide conditions. Therefore the variation in the tides is important to consider, with attention on spring tides and perigean spring tides (king tides) which influence the elevations of extreme sea-levels. King tides were at their maximum around 2015 due to lunar phase orbital forcing which experience shifts over approximately 60 year periods (W. de Lange, personal communication, February 2, 2018). It is expected that the magnitude of king tides will be declining over the next 60 years. This could potentially result in a period of neutral sea-levels, with a spike in higher sea-levels from around 2075 onwards. The role of SLR along with VLM are important to consider as they will influence what level of relative sea-level is experienced at different coastal environments.

3.8 Summary of Key Points

- Storm surges are generally larger inside Tauranga Harbour, compared to the open coast at Moturiki Island.
- Storm surge at locations within the harbour are the result of locally generated conditions.
- Storm surge is largest at Omokoroa, Hairini and Oruamatua and lower at Tug Berth and Moturiki.
- In general the extreme value analysis aligns with previous work such as Stephens (2017) however due to the application of different techniques, this study provides lower extreme sea-level elevations from the distribution.
- The WASP and UoC hindcasts represent storm surge at Moturiki reasonably well, however underestimate many extreme events.
- The 100 year ARI (0.01% AEP) produced storm surge values of 0.34 m at Moturiki, 0.50 m at Tug Berth, 0.59 m at Oruamatua, 0.64 m at Hairini, and 0.75 m at Omokoroa.
- The large storm surge event on the 5th January 2018 has an estimated return period of between 20 years at Omokoroa up to 200 years at Tug Berth. This highlights that Omokoroa experiences higher sea-levels.

Chapter Four

Historical Reconstructions and Qualitative Data

Due to short records, estimates of extreme sea-levels (e.g. 50 or 100 year return periods) are hard to validate without the use of other methods. Techniques used by councils include oral histories, and photographic evidence to fill in for missing long term records. In this Chapter, historical newspaper articles were searched, documenting extreme events and sea-levels in Tauranga Harbour. Newspaper searches were carried out at the Tauranga Public Library. The papers included The Bay of Plenty Times (BOPT), Katikati Advertiser, photo news and historic photographic database. Online newspaper articles were also searched, consisting the BOPT, Sunlive, Stuff and the New Zealand Herald. Searching was conducted using both microfilm and original newspapers. Newspaper sections for important events were scanned and saved. Microfilm sections were cropped, saved and named.

In addition to newspaper records, visual documentation was sought from people living around the Harbour. The contact details of multiple local residents around low lying land in Tauranga Harbour were supplied by the BOPRC. Four different landowners agreed to participate in the research, with human ethics approval obtained (see Appendix 2). Sea-level staffs (1 m) were installed at these locations, with the aim of photographic evidence being provided for significant high sea-level events. The additional data on sea-levels around Tauranga Harbour were matched with data from the nearest tide gauges to calculate the return periods of these events. This is a new approach measuring storm-tide amplitude and coastal inundation from photographic evidence. It is useful because it provides additional spatial data on sea-levels around the Harbour, bearing in mind the cost of having sea-level gauges throughout the entirety of Tauranga Harbour is not feasible.

4.1 Surveyed Events from Sea-level Staffs

Table 4-1 describes the locations and height of the sea-level staffs, installed at four locations around the Harbour. The aim of these staffs was for participating landowners to photograph them during high sea-level events. Sea-levels are extracted by calculating the height from the surveyed staff level.

Table 4-1 Location and elevation of the sea-level staffs.

Water level staff	easting	northing	elevation at the base
Pahoia	358671	814017.8	1.03
Omokoroa Golf Course	361192.1	813495.3	1.62
Matua	369396.4	809728.2	0.79
Waimapu	373029.6	803872.6	1.35

The staffs allow the sea-level to be measured at these locations using photographic evidence for validation. The staffs are located at Omokoroa Golf Course, Pahoia, Matua estuary and Waimapu estuary (Figure 4-1).

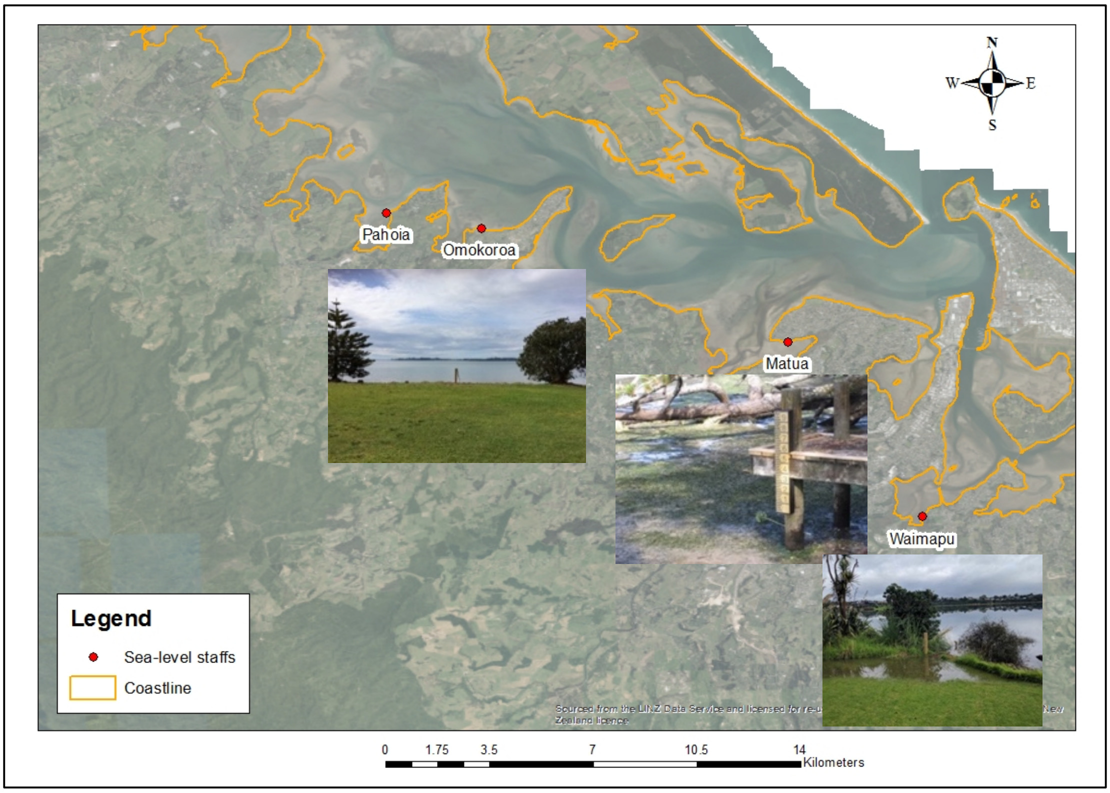

Figure 4-1 Locations of sea-level staffs around Tauranga Harbour.

Photographic evidence of high sea-levels covering the staffs were recieved for multiple events during 2017 and one large event on the 5th January 2018 (see Chapter 5 for full analysis of the 2018 event). The photographed events in 2017 were not extremely large, but have been compared with the TWL and storm surge from the closest sea-level gauge. These events are summarized in Table 4-2.

Table 4-2 Sea-levels for photographed staffs in 2017.

Location	Date	Time (photo)	TWL (m)	Closest gauge	Gauge TWL (m)	High tide	Predicted tide (m)
Waimapu	30/04/17	10:30 am	1.41	Hairini	1.38	11:00 am	0.99
Waimapu	24/06/17	07:50 am	1.40	Hairini	1.43	07:00 am	0.97
Matua	29/03/17	09:20 am	1.15	Omokoroa	1.30	09:00 am	1.04

The results show that sea-level elevations calculated from photographic evidence match reasonably well with measured data from nearby sea-level gauges (except Matua which is not located approximately half way between Tug Berth and Omokoroa). Issues can arise when comparing sea-level elevations from photographic evidence and sea-level gauges due to timing differences in the maximum sea-level. Storm surge associated with these events were low, with maximum values ranging between 0.2 m and 0.25 m (see Appendix 1). Based on the extreme value analysis the estimated return periods for these events are less than a year for the gauges inside Tauranga Harbour, and between five to ten years at Moturiki.

4.2 Surveyed Sea-levels

4.2.1 Cyclone Cook 13th April 2017

Cyclone Cook was forecast to be the most severe since Cyclone Giselle in 1968 which produced the highest storm surge on record of 0.88 m at Sulphur Point in Tauranga Harbour. The sea-level was surveyed at Pilot Bay and Omokoroa wharf based on photographic evidence at high tide on the 13th April 2017. This data along with data from sea-level gauges are used to estimate the return period for this event using the extreme value analysis. The most significant storm surge was predicted for around the time of high tide on 13th April 2017 (Figure 4-2). The Cyclone tracked southward making landfall in the BOP just south of Whangamata around 6 pm on the 13th April 2017. Wind gusts of 209 km/h were recorded at White Island off the coast from Whakatane with gusts exceeding 150 km/h around the BOP. Waves along the BOP coastline reached 6 m, and 200 mm of rain fell in the region (Stuff, 2017).

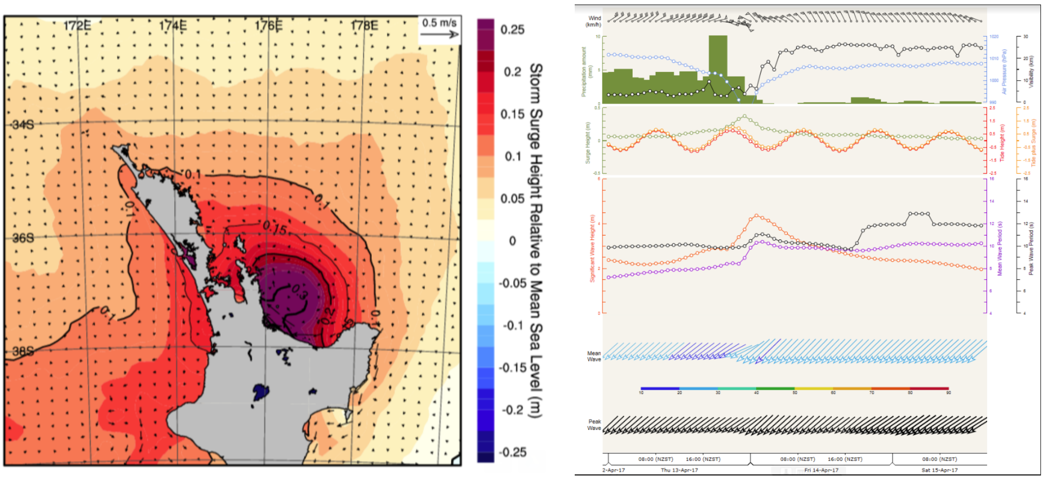

Figure 4-2 Storm surge forecast for Cyclone Cook (Source, EcoConnect).

Table 4-3 summarizes the surveyed sea-levels for Cyclone Cook at Pilot Bay and Omokoroa wharf. Both these locations are located in close proximity to sea-level gauges. Maximum sea-levels are then compared.

Table 4-3 Surveyed sea-level elevations (TWL) for Cyclone Cook (elevation relative to MVD-53).

Location	Date	Time (photo)	TWL (m)	Closest gauge	Gauge TWL (m)	High tide	Predicted tide (m)
Pilot Bay	13/04/17	20:40 pm	1.49	Tug Berth	1.23	20:45 pm	0.81 m
Omokoroa wharf	13/04/17	21:50 pm	1.30	Omokoroa	1.27	10:00 pm	0.92 m

The surveyed sea-level at Pilot Bay was 1.49 m based on photographic evidence taken at 8:40 pm (Figure 4-3). The nearby gauge at Tug Berth recorded TWL of 1.23 m, with the predicted tide being 0.81 m at 8:45 pm. The surveyed level is 0.26 m higher compared to the peak gauge recording at Tug Berth, which likely represents human error and/or the inclusion of effects from waves in the survey.

The surveyed sea-level at Omokoroa wharf was 1.3 m based on photographic evidence taken at 9:50 pm (approximate time of high tide at this location due to the lag in timing of high tide). This level is 0.03 m higher compared to the peak gauge recording of 1.27 m. The predicted tide at Omokoroa was 0.92 m at approximately 10 pm.

Figure 4-3 Left) Photograph taken at Pilot Bay. Right) Photograph taken at Omokoroa wharf.

Maximum sea-levels at high tide on the night of the 13th April 2017 are plotted in Figure 4-4 (interpolated hourly). The sea-level was highest at Hairini, Oruamatua and Omokoroa. The sea-level at Tug Berth and Moturiki was lower. The maximum sea-level occurred earliest at Moturiki and latest at Omokoroa due to the lag in the timing of high tide in the upper parts of Tauranga Harbour.

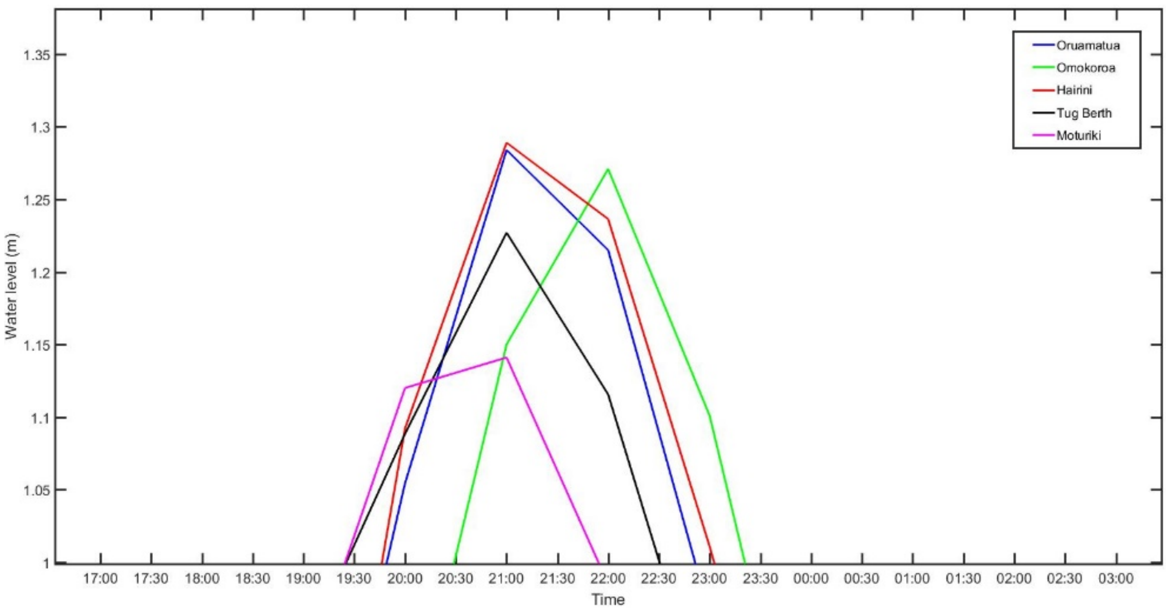

Figure 4-3 Hourly sea-level data at high tide on 13 April 2017 (Cyclone Cook).

The anticipated storm surge from Cyclone Cook was not as large as predicted, with a maximum of 0.33 m at Oruamatua at approximately 7 pm (Figure 4-4). The estimated return periods from the extreme value analysis are 8 years at Moruriki, 5 years at Oruamatua, 3 years at Tug Berth, 1 year at Omokoroa and less than 1 year at Hairini. No coastal inundation occurred however the event had the ability to cause inundation of low lying areas around Tauranga Harbour. It is likely that the lower storm surge resulted due to the faster tracking and rapid progression of the cyclone. Cyclone Cook tracked quickly over New Zealand, resulting in lower rainfall in comparison to some of the previous cyclone impacts. The system was compact with the strongest winds being located within a narrower swath.

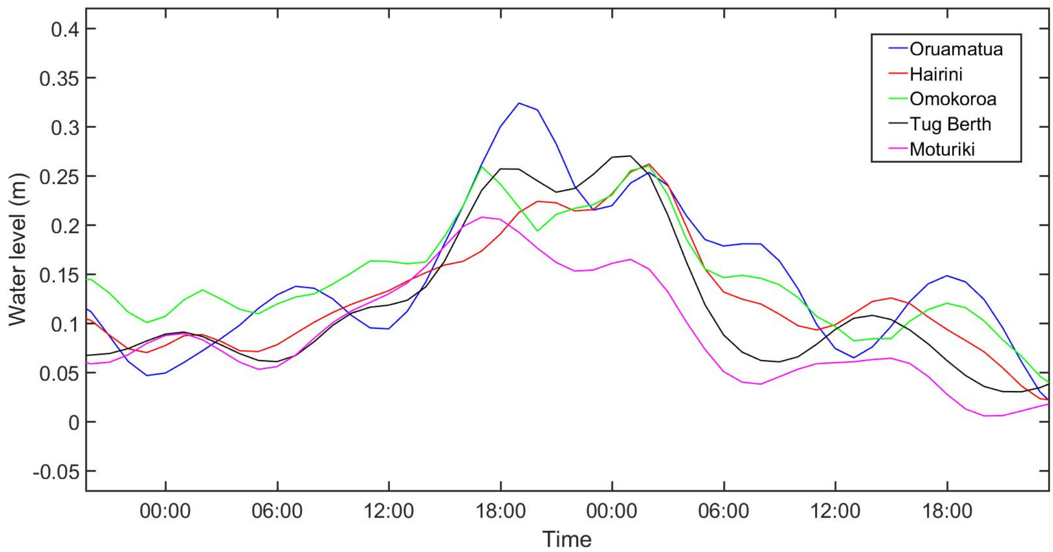

Figure 4-4 Measured storm surge for Cyclone Cook on the night of 13th April 2017.

4.2.2 January 2011 Event

Tauranga Harbour experienced high sea-levels on the 23rd January 2011 when a low pressure system coincided with red alert king tide (2 m) conditions. Photographic evidence from the BOPT was used to survey the sea-level which damaged the Matua walkway (Figure 4-5). The Matua walkway was completely covered by water passing over to a historic paddock owned by Des Ferrow (Bay of Plenty Times, 25 January 2011). The system was generated in the tropics near New Caledonia, however left before developing into a larger tropical cyclone. Strong onshore winds were experienced along the north-east coast of the north Island as the system approached, with the most significant wind set-up influencing the

Coromandel and Bay of Plenty. Coastal inundation was enhanced by strong northerly winds and high rainfall (Bay of Plenty Times, 25 January 2011).

CLOSED INDEFINITELY: The council politely apologises for the damaged Matua walkway between the Shaw St Reserve and the bottom of Otumoetai Rd.

Figure 4-5 Damage to the Matua walkway (photograph source, Joel Ford and Claire Fraser) (Bay of Plenty Times, 25 January 2011).

Table 4-4 summarizes the surveyed sea-level on the Matua walkway for this event (the base of the footpath was surveyed and represents the TWL, as seen from the photographic evidence). The survey of the footpath is likely to incorporate effects from waves to an unknown degree, explaining why the surveyed elevation was 17 cm higher compared to the maximum recorded sea-level at Tug Berth.

Table 4-4 Surveyed sea-level (TWL) at the Matua walkway for the January 2011 event.

Location	Date	Northing	Easting	TWL (m)	Closest gauge	Gauge TWL (m)	High tide	Predicted tide (m)
Matua walkway	24/01/11	371011	810991.6	1.48	Tug Berth	1.31	11:55 am	0.99

Some other known locations that experienced coastal inundation during the event were Ferguson Park’s boat ramp, the Omokoroa golf course and the Silver Birch Holiday Park. The Waikareau Estuary margins were almost completely inundated (Figure 4-6). These locations are low-lying and are considered more vulnerable to inundation during extreme events.

Figure 4-6 King tide on the 24th January 2011, causing inundation along the Waikareau walkway (photo source, Joel Ford and Claire Fraser) (Bay of Plenty Times, 25 January 2011).

Storm surges are plotted for the sea-level gauges for late January 2011, showing the presence of three surges separated by approximately five days each (Figure 4-7). The highest storm surge occurred on 23rd January, being highest at Oruamatua (0.5 m), followed by Omokoroa (0.48 m), and Hairini (0.43 m) around 04:00 am. Storm surge was lower at Tug Berth and Moturiki with values of 0.33 m and 0.28 m respectively. Based on the extreme value analysis this event has an estimated return period of approximately 30 years at Oruamatua and Moturiki, 20 years at Omokoroa and Hairini, and 10 years at Tug Berth.

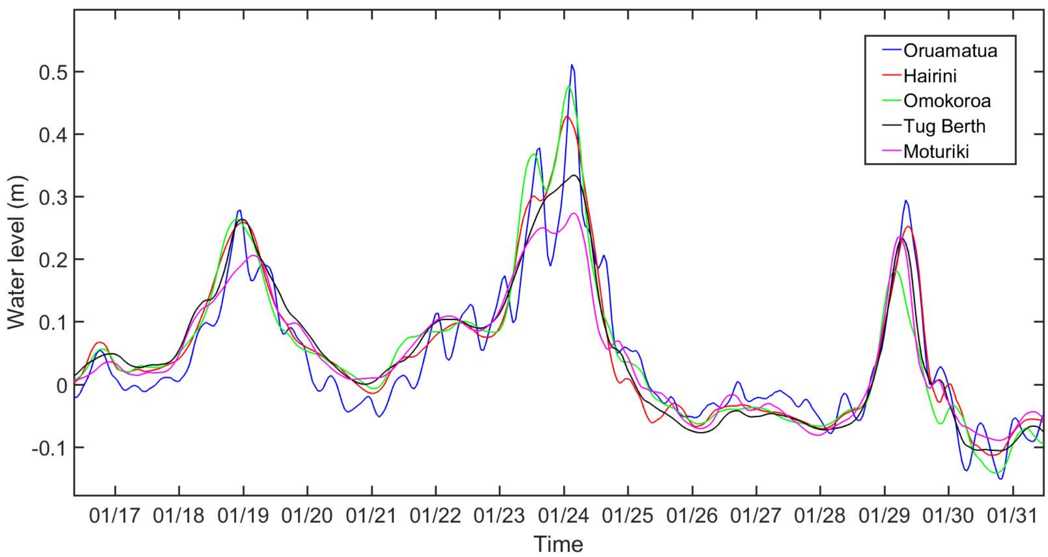

Figure 4-7 Storm surges recorded at the sea-level gauges for the events in late January 2011.

4.3 Summary of key points

- Sea-level staffs can be useful measuring tools, which provide additional spatial data to sea-level gauges.
- The storm surge produced by Cyclone Cook was smaller than predicted, with maximum value of 0.33 m at Oruamatua. Based on the extreme value analysis, this event has an estimated return period of 8 years at Moruriki, 5 years at Oruamatua, 3 years at Tug Berth, 1 year at Omokoroa and less than 1 year at Hairini.
- The survey of sea-levels based on Cyclone Cook had a maximum elevation of 1.49 m at Pilot Bay. This level is considerably higher than the recorded sea-level at the nearby Tug Berth gauge, therefore waves are likely incorporated into the surveyed elevation. The survey at Omokoroa wharf matches more closely to the Omokoroa gauge, indicating wave energy could have entered the entrance causing significant setup around the entrance.
- A low pressure system coincided with king tide conditions on the 24th January 2011, causing high sea-levels in Tauranga Harbour. The surveyed level of 1.48 m is based from photographic evidence from a historical newspapers. It should be noted this is considerably higher than the measured TWL of 1.31 m at Tug Berth.
- Storm surges vary depending on the nature of tropical cyclones/storm, and their track relative to Tauranga Harbour. Cyclone Cook was forecast to be the most significant since the category 4 Tropical Cyclone Gisele in 1968. Due to the fast progression and track of the cyclone, the resulting sea-level was not as high as expected given the spring tide conditions.
- Oral histories, photographic evidence and historic newspapers provided valuable information on extreme sea-levels in Tauranga Harbour, identifying some low-lying areas which are vulnerable to coastal inundation.

Chapter Five

King Tide and Sub-Tropical Storm on the 5th January 2018

Tauranga Harbour experienced significant coastal inundation when a king tide coincided with a sub-tropical storm which passed over the BOP on the 5th January 2018. Special attention should be made to weather forecasts to identify low barometric pressure systems that might coincide with red alert days when the tides are higher than usual. During these times coastal hazards from storm surges are increased, with the potential for coastal inundation of low lying (and gradient) land. This Chapter covers the analysis of extreme sea-levels at the gauges, along with surveyed elevations of extreme sea-levels around Tauranga Harbour and wave height calculations.

5.1.1 Key investigation questions

1. How did the storm surge change within the different arms of the estuary?
2. Were differences in storm surge related to the wind direction and fetch?
3. What was the wave run-up amplitude of the tide and surge?
4. How did this event compare with other large historical events?

The NIWA weather report on 4th January 2018 showed the low pressure system with a clockwise spinning cloud formation which was categorized as a 2/3 tropical cyclone with lowest barometric pressures reaching approximately 970 hPa at the centre (Figure 5-1). The storm tracked southward and slightly west of the North Island, with the largest effects impacting the BOP on the 4th and 5th January. During the passage of the storm Tauranga Harbour was subject to periods of high rainfall and strong persistent winds from the north and north east. The Bay of Plenty Times (Saturday 6 January 2018) reported, "people in low-lying coastal areas were advised to consider self-evacuating as king tides caused flooding throughout the region yesterday. Tent sites were under water at Silver Birch Holiday Park on Turret Rd. The Wairoa River in Te Puna broke its banks and flooded Te Puna Station Rd. Parts of Hairini Bridge were also closed as water lapped across the road and businesses in Judea were flooded. At the peak of the swell early yesterday afternoon, wave heights were reaching 7.6 m at the Port of Tauranga's A-buoy off the entrance to Tauranga Harbour. Matua resident George Corban said water in the Matua Estuary was the highest he had seen, having lived in the area since 1964".

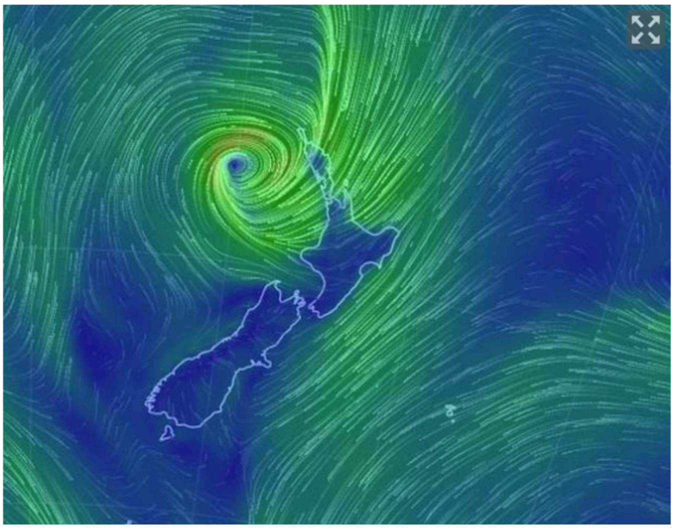

Figure 5-1 Weather map for 4pm Thursday 4 January 2018 (photo/Earth.nullschool.net).

Atmospheric pressure data from Totara St, Mount Maunganui, was obtained from the BOPRC. Atmospheric pressure reached a low of 990 hPa at 3:00 pm, 5 January 2018 (Figure 5-2).

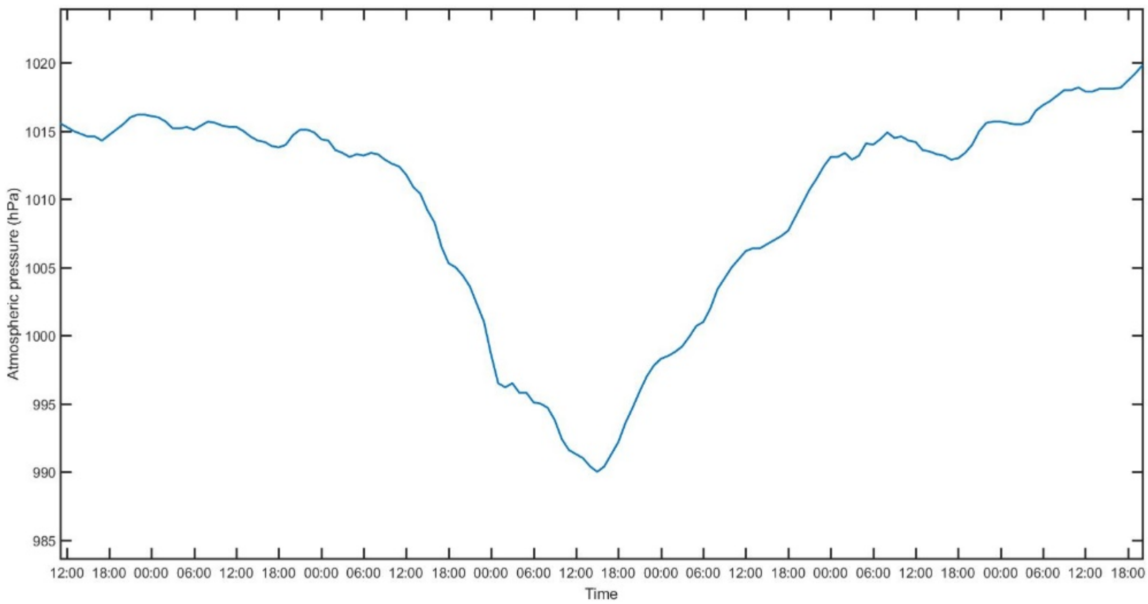

Figure 5-2 Atmospheric pressure recorded at Totara St, 5 January 2018 (operated and maintained by the BOPRC).

Red alert days for king tides were forecast from the 1st to 7th January 2018. On the 4th January, strong E-NE winds with peak gusts of 67km/h were recorded by MetService, accompanied by 62.4 mm of rain. On Friday 5th January the rain had eased however the wind direction changed slightly and started blowing strongly from the north. A MetService spokesman reported the average wind speed on Friday was 50 km/h, with the highest wind gust reaching 80 km/h at 11 am (Bay of Plenty Times, 6 January 2018). During high tide that morning (approximately 10:40 am) Tauranga Harbour was impacted by coastal inundation at many low lying locations.

Wind data from Totara St was obtained from the BOPRC. This was corrected and scaled due to wind speeds being significantly lower in comparison to wind data from Tauranga Airport from 1995 to 2016 which was supplied by MetServive. Wind data was corrected and scaled for Tauranga Airport based on an overlapping regression from wind speed at Totara St, to calculate data at Tauranga Airport for the period 1995 to end of January 2018 (see Chapter 6 for more detail). Wind speed increased throughout the day on 4th January. The highest wind speeds occurred around midday on 5th January, with winds between 50 to 60 km/h (Figure 5-3).

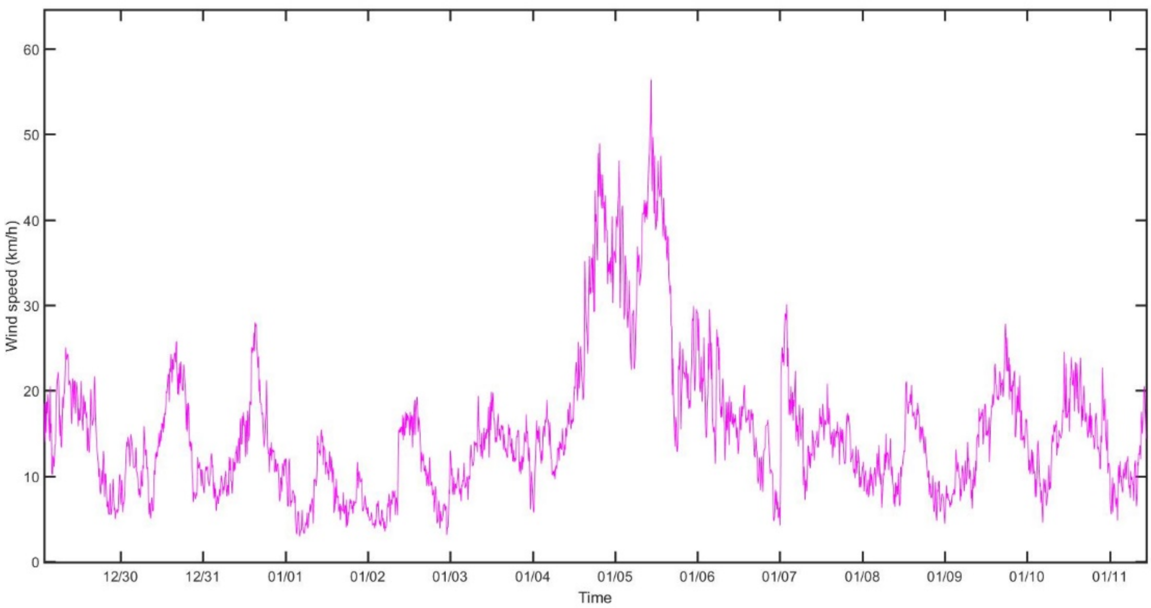

Figure 5-3 Corrected wind speed (Tauranga airport).

5.1.2 Sea-level Gauge Recordings

Raw sea-level data are plotted for high tide on the morning of 5th January 2018 (Figure 5-4). The sea-level gauge at Omokoroa failed at 9:25 am on 5th January 2018. Therefore the peak level was not recorded at this site and would have likely been higher if the sensor did not fail.

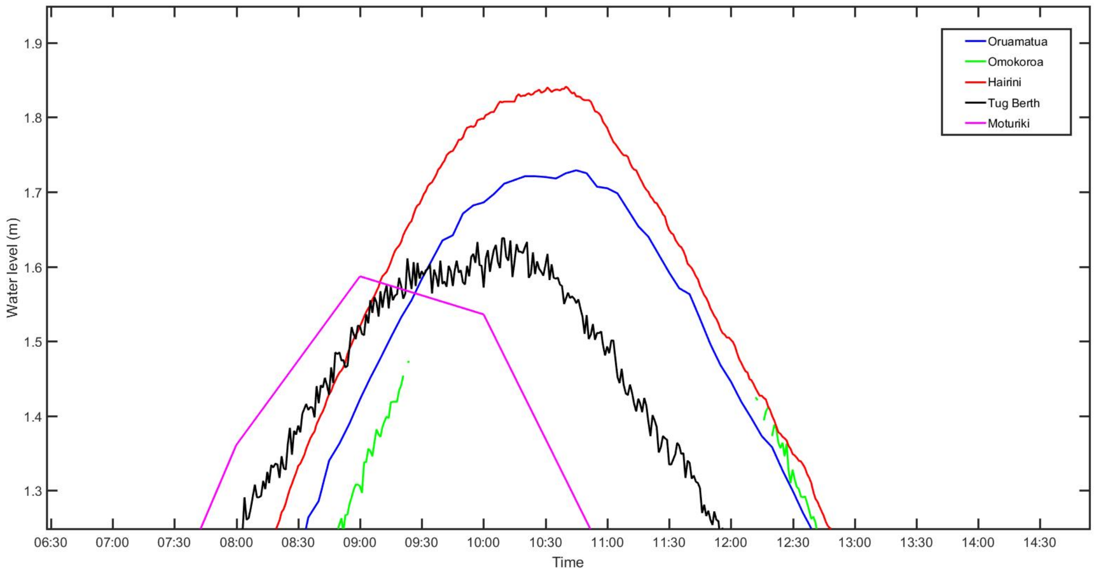

Figure 5-4 Measured maximum sea-level at the gauges shown in Figure. Sampling interval is a minute at Tug Berth, Hairini and Omokoroa and five minutes at Oruamatua, and hourly at Moturiki.

Table 5-1 describes the sea-level gauge recordings and skew surge. The maximum sea-level at the gauges was highest at Hairini, reaching 1.84 m at 10:40 am. This was 0.77 m above the predicted tide of 1.07 m. The maximum level at Oruamatua was 1.73 m at 10:45 am. This was 0.64 m above the predicted tide of 1.09 m. The maximum level at Tug Berth was 1.64 m, occurring earlier at 10:09 am. This was 0.62 m above the predicted tide of 1.02 m. The maximum level at Moturiki was 1.64 m which occurred earliest at 9:10 am. This was 0.55 m above the predicted tide of 1.09 m.

Table 5-1 Sea-level gauge recordings, 5 January 2018.

Gauge locations	Gauge TWL (m)	Time	Projected MSL by 2020 (m)	Predicted tide (m)	Skew surge (m)
Moturiki	1.64	09:10	0.13	1.09	0.55
Tug Berth	1.64	10:09	0.10	1.02	0.62
Hairini	1.84	10:40	0.19	1.07	0.77
Oruamatua	1.73	10:45	0.20	1.09	0.64
Omokoroa	Sensor fail	09:25	0.18	1.03	N/A

Two storm surge peaks were observed during the event (Figure 5-5). The first peak occurred in the early hours on 5 January, and was slightly smaller in comparison to the second peak which occurred around midday. Storm surge was smallest at Moturiki (i.e. outside Tauranga Harbour). The first surge peak was highest at Omokoroa, however the sensor failed around 9:25 am during the incoming tide and therefore the second surge peak would have likely been higher.

The largest storm surge was recorded at Hairini, measuring 0.64 m at 2 pm (Figure 5-5). This is the largest storm surge measured for the sea-level record at Hairini from 2002 to 2018. Both Tug Berth and Omokoroa sensors recorded maximum storm surges of 0.57 m, at 1 pm and 3 pm respectively. This is the largest surge recorded at Tug Berth (for the period 1989 to 2018, therefore excluding Cyclone Gisele that occurred in 1968) and the second largest surge recorded at Omokoroa for the record from 2000 to 2018. The Oruamatua sensor recorded maximum storm surge of 0.56 m at 2 pm. This is the second largest surge recorded at Oruamatua for the sea-level record from 2001 to 2018. The Moturiki sensor recorded the smallest maximum storm surge of 0.29 m at 11 am. This is the 25th largest surge recorded at Moturiki for the period 1974 to 2018.

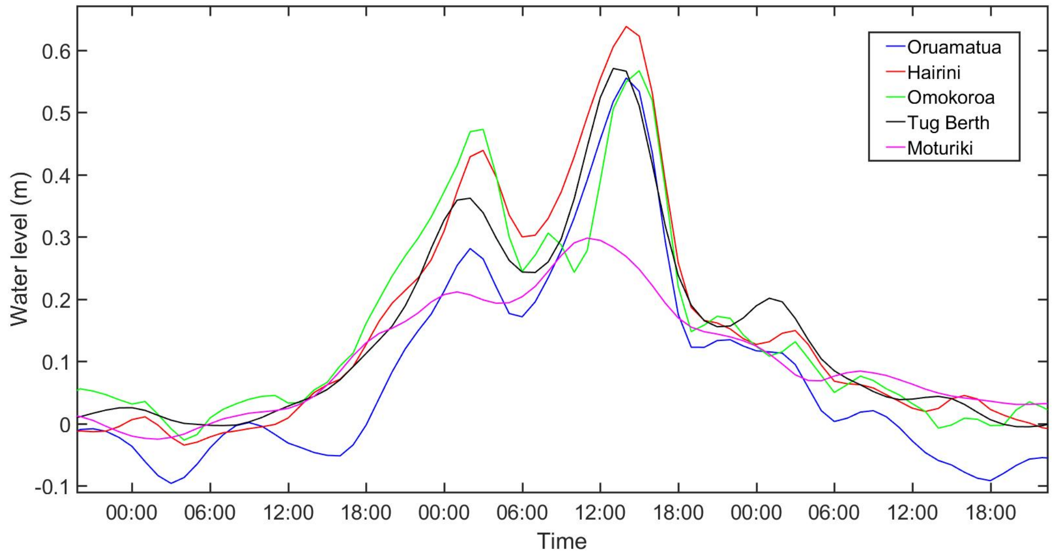

Figure 5-5 Comparison of storm surge at sea-level gauges. Note: Omokoroa gauge failed during high tide.

5.2 Storm Surge Return Period

The annual exceedance probabilities (AEP) for the January 5th event have been estimated using the extreme value analysis (see Chapter 3). The storm surge AEP for this event ranges between 0.02% (50 year ARI) at Moturiki, to 0.005% (200 year ARI) at Tug Berth. The 0.64 m surge at Hairini equates directly to the 0.01% AEP (100 year ARI). The 0.57 m surge at Tug Berth equates to the 0.005% AEP (200 year ARI), and 0.56 m event at Oruamatua equates roughly to between 0.02% and 0.01% AEP (50 to 100 year ARI). The 0.29 m surge at Moturiki equates to the 0.02% AEP (50 year ARI). Due to the sensor failing at Omokoroa, the 0.57 m recorded surge would have likely been higher and likely has not been correctly matched to the corresponding AEP.

5.3 Surveyed Sea-level around Tauranga Harbour

Field surveys were carried out on the 15th and 24th January 2018, to survey the elevation of extreme sea-levels. Additional surveys were carried out on the 22nd May and 7th June 2018. Surveys were conducted using RTKGPS equipment with points based on evidence of a well-defined flotsam line (either physical or photographic). Eyewitness recollections and photographic evidence at high tide were also used at two locations where the flotsam had been cleared, including

Pilot Bay and the Harbourside Restaurant. Eyewitness evidence at Pilot Bay validates the survey is representative of the seas reach during the event. The survey at Harbourside Restaurant is based on an inundation photograph in the carpark around high tide, however the sea-level may have reached a higher elevation than what was surveyed. Measurements were checked at appropriate Land Information New Zealand (LINZ) survey marks around Tauranga Harbour. Northing, easting and elevation for multiple points at the same location were averaged for each location. A total of 24 sites were surveyed around Tauranga Harbour, from Pahoia in the north-west, around the shoreline to Pilot Bay in Mount Maunganui (Figure 5-6). Surveyed sea-level results are summarized in Table 5-2. Photographic evidence for all surveyed locations are provided in Appendix 3.

1. Pahoia (eye witness flotsam and photographs)
2. Omokoroa Golf Course (eye witness flotsam and photographs)
3. Omokoroa domain (flotsam photographs)
4. Waitui Reserve (flotsam photographs)
5. Wairoa River (flotsam photographs)
6. Matua, south facing (eye witness flotsam and photographs)
7. Ferguson Park, western (flotsam photographs)
8. Ferguson Park, eastern (physical flotsam)
9. Harbour Drive, Otumoetai (physical flotsam and photographs)
10. Harbour Drive, Otumoetai (physical flotsam)
11. Waikareau walkway, north-western side (flotsam photographs)
12. Waikareau walkway, southern side (flotsam photographs)
13. Sulphur Point (flotsam photographs)
14. Harbourside Restaurant, Tauranga (photographs)
15. Memorial Park, Tauranga (flotsam photograph)
16. Grace Rd, Tauranga (inundation photograph)
17. Silver Birch Holiday Park boat ramp, Waimapu estuary (physical flotsam)
18. Waimapu estuary, south east side (physical flotsam)
19. Hairini Bridge (physical flotsam)
20. Maungatapu Marae (physical flotsam)

21. Rotary Park, Maungatapu (flotsam photograph)
22. Welcome Bay, western sheltered site (flotsam photograph)
23. Welcome Bay, Tye Park (flotsam photograph)
24. Pilot Bay, southern carpark (eye witness and photograph)

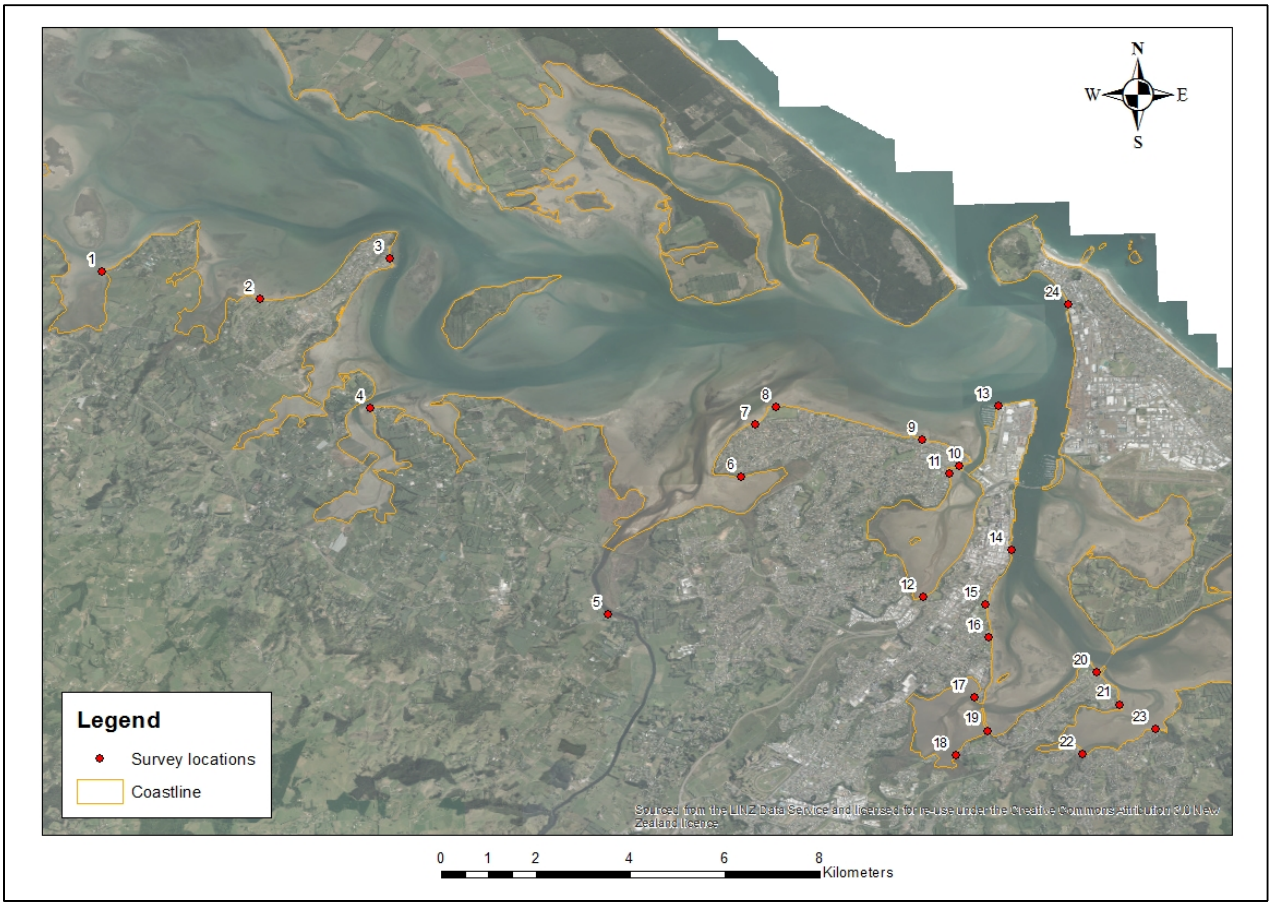

Figure 5-6 Map of the surveyed sea-levels for the event on the 5th January 2018.

Table 5-2 Surveyed sea-levels around Tauranga Harbour based on 5th January 2018 (heights relative to MVD-53).

Site	Location	northing	easting	Surveyed TWL (m)	Closest gauge	Gauge TWL (m)	Predicted tide (m)	Skew-surge (m)	Distance from entrance (km)	Type	Comments
1	Pahoia	814010.8	358730.2	1.97	Omokoroa	sensor failed	1.08	0.89	16	Flotsam	N facing exposed shoreline
2	Omokoroa golf course	813224.3	361091	1.96	Omokoroa	sensor failed	1.08	0.88	13.5	Flotsam	N facing exposed shoreline
3	Omokoroa domain	814237	363491.2	1.78	Omokoroa	sensor failed	1.08	0.7	10.5	Flotsam	E facing exposed shoreline
4	Waitui Reserve	811149.4	363178.6	1.32	Omokoroa	sensor failed	1.08	0.24	10.8	Flotsam	SW facing sheltered shoreline
5	Wairoa River	806788.8	367182.8	1.88	Omokoroa	sensor failed	1.08	0.8	10	Flotsam	Wairoa River bank by Wairoa Bridge
6	Matua	809735.9	369447.6	1.68	Omokoroa	sensor failed	1.08	0.6	7.2	Flotsam	S facing sheltered shoreline
7	Ferguson Park	810831.1	369669	1.74	Tug Berth	1.64	1.03	0.71	5	Flotsam	N facing exposed shoreline
8	Ferguson Park	811166.9	369993.2	1.75	Tug Berth	1.64	1.03	0.72	4.6	Flotsam	N facing exposed shoreline
9	Harbour Drive	810312.1	372627.8	1.71	Tug Berth	1.64	1.03	0.68	3.5	Flotsam	NE facing exposed shoreline
10	Chapel St	810006.9	373065.7	1.68	Tug Berth	1.64	1.03	0.65	4	Flotsam	N facing exposed shoreline
11	Waikareau NW side	809854.5	372860.9	1.59	Tug Berth	1.64	1.03	0.56	4.2	Flotsam	E facing sheltered shoreline
12	Waikarea S side	807159.2	372428.6	1.76	Tug Berth	1.64	1.03	0.73	6.8	Flotsam	N facing exposed shoreline
13	Sulphur Point	811231.5	373704.6	2.04	Tug Berth	1.64	1.03	1.01	2.7	Flotsam	N facing exposed shoreline
14	Harbourside restuarant	808178.9	373937.6	1.64	Tug Berth	1.64	1.03	0.61	5.9	Photograph	E facing moderately exposed shoreline
15	Memorial Park	807061.4	373518.9	1.83	Hairini	1.84	1.07	0.76	7.3	Flotsam	E facing moderately exposed shoreline
16	Grace Rd	806347.7	373565.3	1.77	Hairini	1.84	1.07	0.7	7.8	Photograph	E facing moderately exposed shoreline
17	Holiday Park	805035	373355.9	1.64	Hairini	1.84	1.07	0.57	9.5	Flotsam	S facing sheltered shoreline
18	Waimapu	803872.8	373043.2	1.81	Hairini	1.84	1.07	0.74	10.5	Flotsam	NW facing moderately exposed
19	Hairini Bridge	804506.8	373519.7	2.03	Hairini	1.84	1.07	0.96	9.75	Flotsam	N facing land - low lying Hairini bridge
20	Maungatapu Marae	805624.9	375411.1	1.85	Oruamatua	1.73	1.09	0.76	8.75	Flotsam	NE facing moderately exposed
21	Rotary Park	804945	375739.4	1.85	Oruamatua	1.73	1.09	0.76	9.5	Flotsam	NE facing exposed shoreline
22	Welcome Bay	803886.9	375141.4	1.7	Oruamatua	1.73	1.09	0.61	10.9	Flotsam	N facing moderately sheltered shoreline
23	Tye Park, Welcome Bay	804415.4	376375.2	1.84	Oruamatua	1.73	1.09	0.75	10.3	Flotsam	N facing exposed shoreline
24	Pilot Bay	813408.5	374879.7	2.11	Tug Berth	1.64	1.03	1.08	1.5	Eyewitness	W facing exposed - close to entrance

5.3.1 Survey Results

All surveyed elevations are based on heights above MSL MVD-53. The sub-tropical storm that coincided with a king tide on the 5th January 2018 produced surveyed sea-levels around Tauranga Harbour between 1.32 m to 2.11 m (Figure 5-7). The surveyed elevations are based mainly from flotsam lines and include added effects from wave run-up (therefore they relate to the storm tide elevations). These are compared to the TWL from the closest sea-level gauge to investigate the likely influence on recordings of wave setup and run-up.

The highest surveyed sea-level was at the southern carpark on Pilot Bay, reaching 2.11 m. Sea-level between 2 to 2.1 m were recorded at the northern end of Sulphur Point and southern end of the Hairini Bridge. Pahoia and the Omokoroa Golf Course also had high sea-levels, reaching 1.97 m and 1.96 m respectively. The majority of locations had surveyed sea-levels between 1.7 m to 1.9 m. In general, sea-level was higher along northerly facing shorelines, especially exposed locations. The sea-level was lower at sheltered locations (i.e. facing south or protected by protruding land) (Figure 5-7). This included the Silver Birch Holiday Park, sheltered Welcome Bay site, north western corner of the Waikareau estuary, Chapel St, Bay St, and Waitui Reserve. The lowest sea-level was surveyed at Waitui Reserve, reaching 1.32 m.

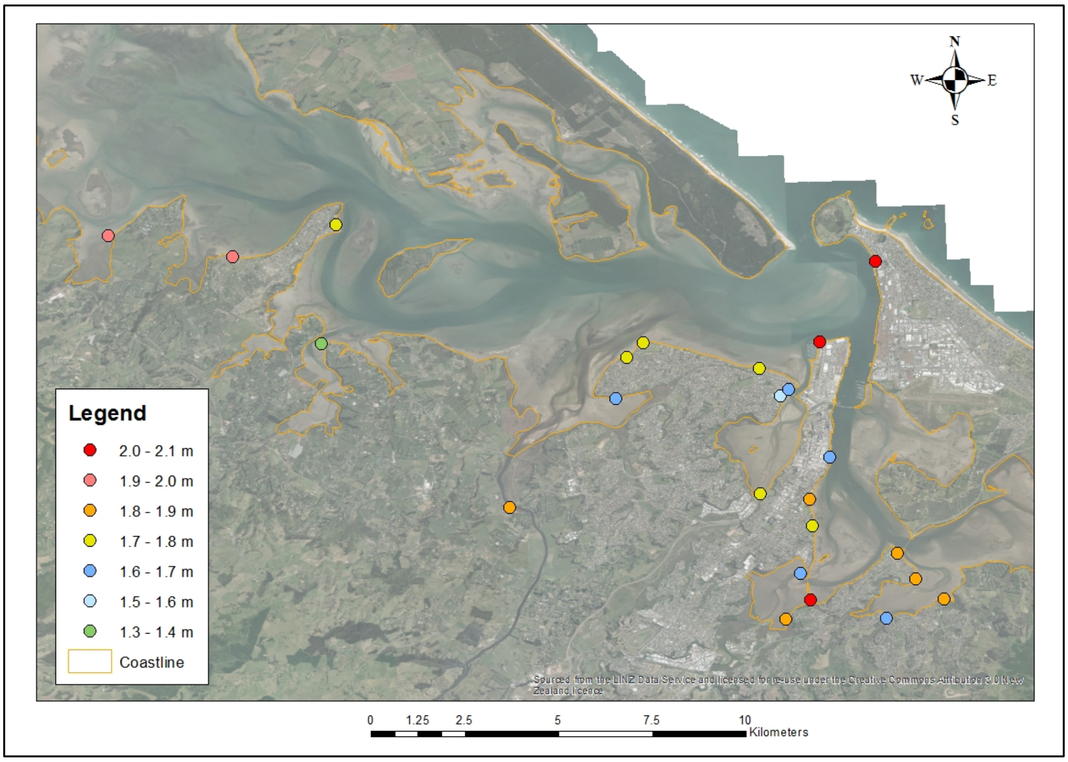

Figure 5-7 Map showing the surveyed TWL (MVD-53) around Tauranga Harbour for the event on 5th January 2018.

5.4 Additional data from sea-level staffs

Four sea-level staffs were installed around Tauranga Harbour on low lying land (see Chapter 4). These staffs aimed to provide additional data on extreme sea-levels for events such as the one on 5th January 2018. Photographic evidence of the sea-level staffs were obtained for Matua and Omokoroa golf course. During the event two staffs were washed away, with one of them reinstalled since. Details of the sea-levels extracted from the photographs are summarized in Table 5-3. Both of these locations were also surveyed based on flotsam lines following the event.

Table 5-3 Sea-levels calculated from staffs on 5th January 2018.

Location	TWL (staff) (m)	Time of photo	Closest gauge	Gauge TWL (m)	Predicted tide (m)	Time
Waimapu	1.67	11:15 am	Omokoroa	Sensor failed	1.09 m	11:00 am
Omokoroa Golf course	1.8-1.9 approx.	10:40 am	Omokoroa	Sensor failed	1.09 m	11:00 am

The TWL on the sea-level staff at Matua was 1.67 m (Figure 5-8). This matches well with the surveyed flotsam level of 1.68 m, showing how photographic evidence of sea-level staffs can be a reliable tool for measuring sea-level. Photographic evidence of the sea-level staff at Omokoroa golf course was less reliable to measure. This was due to crashing waves on the staff making it difficult to measure the still sea-level (Figure 5-8). Instead a level was estimated at between 1.8 m to 1.9 m based on the photograph time. The photograph was taken slightly before maximum sea-level was reached at this location. The survey at Omokoroa golf course showed sea-level reached 1.96 m.

Figure 5-8 Left) Bay St, Matua at 11:15 am. Right) Omokoroa golf course at 10:40 am.

5.5 Storm Tide and the influence of Waves

5.5.1 Skew-surge

Skew-surge was calculated by subtracting the predicted tide (from closest gauge) from the surveyed TWL. Skew-surge was plotted against distance from the southern entrance (Figure 5-9). The results are not statistically significant but show a general trend that skew-surge is greater in upper parts of Tauranga Harbour for this event. There are some outliers such as Pilot Bay and Sulphur Point which are located closest to the entrance, however have the largest surveyed elevations and skew-surge. The higher sea-level at these locations could be due to increased exposure from wind and waves on the open coast which are influencing these locations near the entrance. Waitui Reserve is another outlier which had the lowest skew-surge of 0.24 m, located 10.8 km from the entrance. This may be explained by the sheltered location of this site.

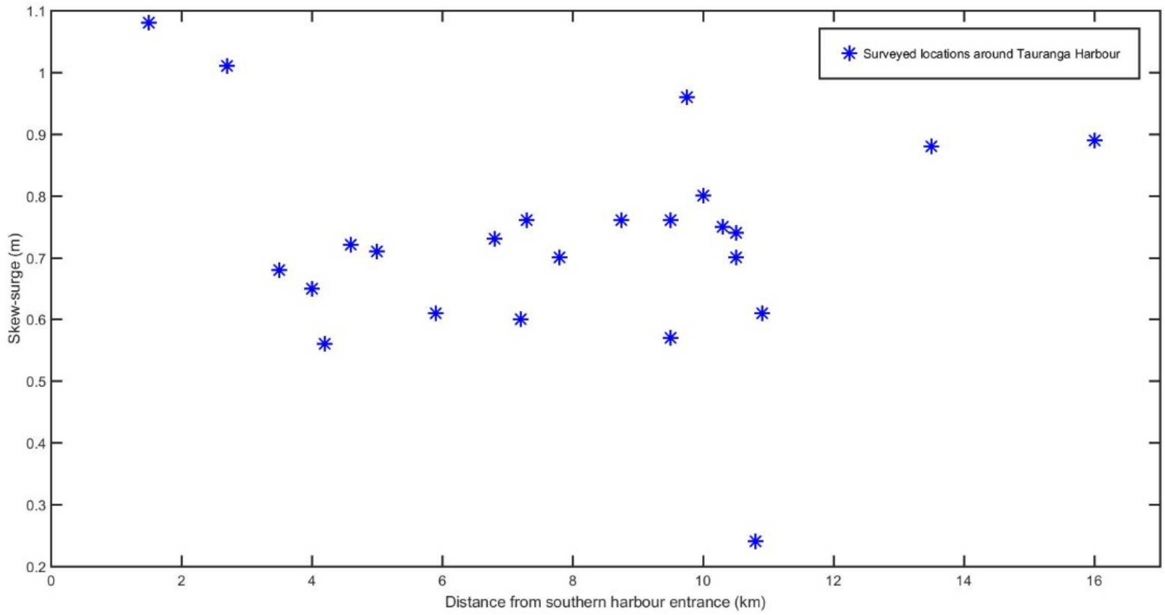

Figure 5-9 Skew-surge (TWL - predicted tide from closest sea-level gauge) plotted against distance from the southern entrance, based on the surveyed locations. Statistics: r^2=0.01, P-val=0.64.

5.5.2 Wave Height Calculations

Skew-surge includes added effects from waves. Waves at each surveyed location was investigated using the TMA wave spectrum. This method was chosen due to the reliability of wave height calculations in shallow water (Hughes, 1984). The variables included wind speed, fetch, storm duration and water depth to calculate significant wave height from the TMA spectrum. There are some assumptions that should be noted when applying the TMA spectrum. Wind speed is assumed to be constant for the period generating waves to equilibrium. The water depth is also set as a constant, assuming the bathymetry is smooth with no complex topography which could influence waves at a greater extent (Hughes, 1984).

During the event on the morning of 5^{th} January, the wind was blowing from the north. The fetch was averaged from 355 degrees to 5 degrees (five degrees either side of north) to incorporate slight changes in wind direction around this time. The averaged wind speed on the 5^{th} January 2018 was 50 km/h (13.9 m/s). The water depth is shallow throughout Tauranga Harbour (excluding main channels) and was estimated as 4 m for all locations. Wind speed should be obtained at an elevation of 10 m, however it should be noted the Totara St wind station is located at 3 m. This difference is small and values are still considered appropriate for this analysis. Table 5-4 details the wave height calculations based on fetch, wind speed, storm duration and water depth.

Table 5-4 Significant wave heights calculated using TMA spectrum for surveyed locations around Tauranga Harbour.

Location	Fetch, north (km)	Wind speed (m/s)	Water depth (m)	Sig wave height (Hmo)	Survey TWL MVD-53 (m)	Predicted tide (m)	Distance from entrance (km)	Storm surge (m) (TWL-tide-Hmo)
23 Pahoia Beach Rd	9.00	13.9	4	0.33	1.97	1.08	16	0.56
Omokoroa golf course	9.42	13.9	4	0.34	1.96	1.08	13.5	0.54
Omokoroa domain	1.25	13.9	4	0.13	1.78	1.08	10.5	0.57
Waitui Reserve	0.23	13.9	4	0.03	1.32	1.08	10.8	0.21
Wairoa River	0.15	13.9	4	0.03	1.88	1.08	10	0.77
Matua	0	13.9	4	0	1.68	1.08	7.2	0.60
Ferguson Park	2.80	13.9	4	0.19	1.74	1.03	5	0.52
Ferguson Park	2.85	13.9	4	0.19	1.75	1.03	4.6	0.53
Harbour Drive	2.72	13.9	4	0.19	1.71	1.03	3.5	0.50
Chapel St	0	13.9	4	0	1.68	1.03	4	0.65
Waikareau NW side	0	13.9	4	0	1.59	1.03	4.2	0.56
Waikarea S side	1.67	13.9	4	0.15	1.76	1.03	6.8	0.58
Sulphur Point	2.60	13.9	4	0.18	2.04	1.03	2.7	0.83
Harbourside restuarant	0.70	13.9	4	0.09	1.64	1.03	5.9	0.52
Memorial Park	0	13.9	4	0	1.83	1.07	7.3	0.76
Grace Rd	0.71	13.9	4	0.09	1.77	1.07	7.8	0.61
Holiday Park	0	13.9	4	0	1.64	1.07	9.5	0.57
Waimapu	1.51	13.9	4	0.14	1.81	1.07	10.5	0.60
Hairini Bridge	1.59	13.9	4	0.14	2.03	1.07	9.75	0.82
Maungatapu Marae	0.95	13.9	4	0.11	1.85	1.09	8.75	0.65
Rotary Park	1.16	13.9	4	0.12	1.85	1.09	9.5	0.64
Welcome Bay	0.93	13.9	4	0.11	1.7	1.09	10.9	0.50
Tye Park, Welcome Bay	2.03	13.9	4	0.16	1.84	1.09	10.3	0.59
Pilot Bay	0	13.9	4	0	2.11	1.03	1.5	1.08

Wave height was calculated to be higher at locations exposed to larger fetches from the north. The wave height at these more exposed locations is responsible for a considerable amount of the TWL, and has been subtracted from the surveyed TWL, along with the predicted tide to obtain estimated values of storm surge. Storm surge was then plotted against distance from the southern entrance of Tauranga Harbour (Figure 5-10). The results are not statistically significant, however there is a general trend that storm surge values decrease with distance from the entrance. This method assumes wave height was negligible at locations which were not exposed to a northerly fetch.

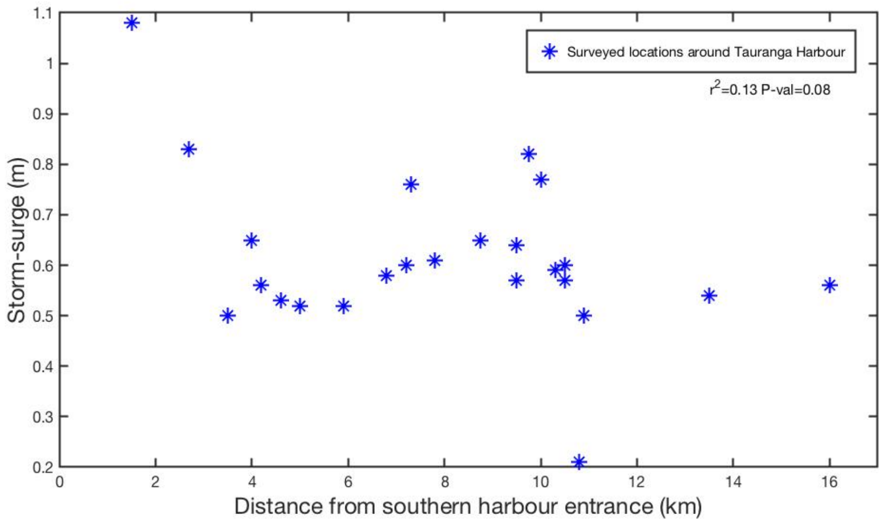

Figure 5-10 Estimated storm surge at the surveyed locations, plotted against distance from the southern entrance. Surge was calculated by subtracting the significant wave height and predicted tide from the TWL.

Significant wave height was calculated to be largest at Omokoroa golf course and Pahoia. These locations both face north into Tauranga Harbour and are exposed to reasonably large fetches from the north to north-west. Pilot Bay is located closest to the entrance however wave height calculations were not considered because it’s not exposed to northerly fetches. Based on eye-witness observations at the time of the event, this is not true as waves were overtopping the southern carpark causing periods of inundation (Figure 5-11). Young (1999) highlights multiple factors which drive wind generated wave fields, including wind speed and direction (including any variation), coastline geometry and water depth. Young, Verhagen & Banner (1995) used a numerical model to show bimodal directional spreading in wind generated waves can result from direct nonlinear energy transfer between waves. Donelan et al., (1985) investigated the effect of fetch geometry on waves, identifying a gradient in the fetch when the land boundary is not perpendicular to the direction of wind. Wave direction can change and start propagating more from the direction of larger fetch, by up to as much as 50°. This could explain why waves were observed at Pilot Bay, even though it is not exposed to a northerly fetch. Instead sea-level could have been forced by winds blowing along the Harbour and causing water to pile up in the southern basin, impacting locations such as Pilot Bay and Sulphur Point. It is reasonable to suggest that external wave energy entered the Harbour through the southern entrance and resulted in higher sea-levels around this location due to enhanced wave set-up. This aligns with the survey of sea-levels which showed the highest elevations were reached at Pilot Bay and Sulphur Point.

Figure 5-11 Waves causing inundation at the southern carpark on Pilot Bay, Mount Maunganui at 10:45 am on the 5th January 2018.

In general, the wave height calculations match observations and photograph evidence (excluding Pilot Bay). This is shown by comparing wave effects at Bay St (Matua) which faces south and was sheltered from the northerly wind, with the exposed site at Omokoroa golf course which experienced larger waves (Figure 5-12).

Figure 5-12 Left) Sheltered south facing site at Bay St, Matua. Right) Exposed north facing site at Omokoroa golf course.

5.6 Comparison with Large Historic Storm Surges

The three large historical storm surge events identified by Gibb (1997) are provided in Table 5-5. Stephens (2017) updated the table with regard to storm surge (most likely storm tide due to inclusion of wave effects) levels, accounting for SLR of 2.1 mm/y. Gibb (1997) uses eye-witness accounts to measure the extreme sea-levels from the large historical events of (i) the unnamed category 4 tropical cyclone on the 2nd February 1936, (ii) the unnamed category 3 tropical cyclone on 6 to 8 March 1954, and (iii) category 4 Tropical Cyclone Gisele on the 10th April 1968.

Maximum storm surge elevations from the surveyed elevations of the three large historical events were approximately 1.1 m to 1.7 m above MVD-53 (Gibb, 1997). Both the 1936 and 1968 events occurred during neap tide conditions (predicted tides 0.74 m and 0.71 m) and therefore extreme sea-levels would have been higher had they coincided with higher tides. In comparison both the 1954 and 2018 events occurred during spring tide conditions (predicted tides 0.94 m and 1.03 m). Maximum surveyed elevations (MVD-53) for these events were 2.36 m, 2.44 m, 2.39 m, and 2.11 m for the 1936, 1954, 1968 and 2018 events respectively. The three large historical storm surges have estimated return periods of 46, 76 and 214 years (AEP of 0.021, 0.012 and 0.005) for the 1936, 1954 and 1968 events respectively. All caused significant coastal inundation of low-lying land around Tauranga Harbour.

The tropical cyclone on the 2nd February 1936 was a category 4 event which occurred during neap tide conditions. The maximum surveyed elevation was 2.36 m above MSL MVD-53 at the rear end of the inundated Omokoroa golf course. Storm tide between survey sites were 1.13 m to 1.62 m above the predicted tide of 0.74 m. The unnamed tropical cyclone of 6th to 8th March 1954 was a category 3 event which occurred during spring tide conditions. The maximum surveyed elevation was 2.44 m at Tilby Point, Ferguson Park. Storm tide were 1.09 m to 1.50 m above the predicted high tide of 0.94 m. Tropical Cyclone Gisele was a category 4 event on 10 April 1968 which occurred during neap tide conditions. The maximum surveyed elevation was 2.39 m at 10 Strange Rd in Matua. Storm tide between surveyed sites were 1.05 to 1.68 m above the predicted high tide of 0.71 m, MSL MVD-53. Both sea-level gauges at Mount Maunganui (Salisbury Wharf) and Tauranga (Sulphur Point) recorded this event, with storm tides of 0.76 m and 0.88 m respectively.

Tauranga Harbour was subject to three closely spaced tropical cyclones between December 1996 and March 1997. Tropical Cyclone Fergus was a category 2 event on the 29th to 31st December 1996, which coincided with neap tide conditions. Fergus produced a peak storm tide of 0.57 m above the predicted tide of 0.64 m, reaching 1.21 m. Tropical Cyclone Drena was a category 2 event on the 10th to 11th January 1997, which coincided with spring tide conditions. Drena produced a peak storm tide of 0.21 m above the predicted tide of 1.04 m, reaching 1.25 m. Tropical Cyclone Gavin was a category 1 (Tropical depression) event on the 10th to 13th March 1997, which coincided with spring tide conditions. Gavin produced a peak storm tide of 0.3 m above the predicted tide of 0.94 m, reaching 1.24 m. This shows how all three events produced different storm tides, however due to the difference in tidal elevations they all produced similar maximum storm tide elevations. If Fergus had coincided with the January spring tide conditions instead, the difference in storm tide elevations would have been significant, reaching 1.61 m (1.04 m + 0.57 m) which could have inundated low-lying land.

In comparison the category 2/3 event on the 5th January 2018 coincided with spring tide conditions. The maximum surveyed elevation was 2.11 m at Pilot Bay. The TWL storm tide at surveyed sites were 0.24 m to 1.08 m above the predicted high tide of 1.03 m at Tug Berth. Storm tides at the sea-level gauges ranged from 0.55 m at Moturiki to 0.77 m at Hairini.

Table 5-5 Three largest historical extreme sea-levels in Tauranga Harbour: 1936, 1954 and 1968 (Gibb, 1997; adapted by Stephens, 2017).

Location	TWL elevation (m MVD-53)	Predicted high tide (m)	*Storm surge(Gibb)* (m)	Tropical Cyclone	MSL (m) (MVD-53)	MSL-adjusted surge (*Gibb*) (m)	Notes
Harbourside restuarant	1.87	0.74	1.13	2 Feb 1936	-0.06	1.19	Up harbour. Relatively small wave fetch
Bathing sheds	2.14	0.74	1.40	2 Feb 1936	-0.06	1.46	The author is uncertain of this location
27 levers Rd	2.27	0.74	1.53	2 Feb 1936	-0.06	1.59	Inland – no wave runup?
Omokoroa golf course	2.36	0.74	1.62	2 Feb 1936	-0.06	1.68	At back of completely inundated golf course. No wave runup?
Grace Rd/Harvey St	2.03	0.94	1.09	6 Mar 1954	-0.02	1.11	Up harbour. Relatively small wave fetch. Inland-no wave runup?
Tilby Point	2.44	0.94	1.50	6 Mar 1954	-0.02	1.52	0.9 m above land surface-true inundation height
Mt Maunganui tide gauge	1.4+	0.64	0.76	10 Apr 1968	0.01	0.75+	Above tide gauge max – true max higher
Tauranga tide gauge	1.59	0.71	0.88	10 Apr 1968	0.01	0.87	
Kulim Park	1.86	0.71	1.15	10 Apr 1968	0.01	1.14	
77 Beach Rd	1.82	0.71	1.11	10 Apr 1968	0.01	1.10	
27 Levers Rd	1.76	0.71	1.05	10 Apr 1968	0.01	1.04	Inland – no wave runup?
10 Strange Rd	2.39	0.71	1.68	10 Apr 1968	0.01	1.67	Higher than others – localised wave runup effects?
Omokoroa golf course	1.91	0.71	1.20	10 Apr 1968	0.01	1.19	

5.7 Summary of Key Points

- The passage of a sub-tropical storm coincided with spring tide conditions on the 5th January 2018, causing coastal inundation around Tauranga Harbour.
- The storm was characterised by low atmospheric pressure reaching 990 hPa at 3 pm, Totara St, Mount Maunganui. The three largest historical tropical cyclones identified by Gibb (1997) were characterized by low pressures between 970 hPa to 990 hPa and strong persistent onshore winds blowing up to 150 km/h.
- Average wind speed was 50 km/h from the north on the 5th January, with maximum gusts of 80 km/h at 11 am.
- The spring high tide was predicted for 1.03 m at Tug Berth, shortly after 10 am.
- The event produced some of the highest storm surges recorded at the sea-level gauges, with a maximum surge of 0.64 m at Hairini. This corresponds to the 0.01% AEP, corresponding to an event exceeded on average once every 100 years. The gauge at Omokoroa failed during the event and therefore extreme sea-levels could not be determined accurately at this location, which is unfortunate as it is known for experiencing some of the highest sea-levels in Tauranga Harbour.
- Surveyed elevations around Tauranga Harbour were based on flotsam lines, which includes the elevation from wave run-up. Elevations reached between 1.32 to 2.11 m above MVD-53. Higher levels were experienced at exposed locations with shorelines facing north-west to north-east. Lower levels were experienced at sheltered locations and shorelines facing south-west to south.
- Extreme sea-levels from the 2018 event are slightly lower but comparable with the three largest historical events. Maximum surveyed elevations (MVD-53) were 2.36 m, 2.44 m, 2.39 m, and 2.11 m for the 1936, 1954, 1968 and 2018 events respectively.
- Significant wave height was calculated using the TMA spectrum for shallow water. Waves were largest at northerly oriented shorelines with

large fetches, including Omokoroa golf course and Pahoia. The method used to calculate wave height assumed wave effects were negligible at locations that did not have northerly fetches. This does not align with eyewitness observations which showed waves had a significant influence at shorelines such as Pilot Bay which faces west into the Harbour.

- The surveyed sea-levels incorporate the combination of storm tide and wave run-up. The highest elevations of 2.11 m and 2.04 m were surveyed at Pilot Bay and Sulphur Point respectively. This indicates external wave energy entered the Harbour with wave set-up and run-up influencing the higher sea-level at these locations.

Chapter Six

The Drivers of Storm Surge and their Dependence on the Southern Oscillation Index

Atmospheric pressure accounts for 50% of the variance in storm surges at Moturiki (Goring, 2006). In New Zealand the average atmospheric pressure is 1014 hPa (de Lange & Gibb, 2000). The theoretical inverse barometer (IB) effect in an ideal ocean is the temporary rise and fall in sea-level based around this pressure, with a drop of 1 hPa corresponding to a 0.01 m rise in sea-level. In this Chapter, detailed weather analysis is undertaken with the aim to determine the influence of atmospheric pressure and wind on storm surge at the sea-level gauges. The remaining variance in storm surge is likely explained by the influence of wave setup and run-up. Goring (2006) reports that wind was not significant in explaining storm surge at Moturiki, however Bell et al (2006) suggests that wind will be significant inside estuaries such as Tauranga Harbour. The first half of the Chapter details the stepwise regression analysis applied to atmospheric pressure and wind data to explain storm surge variability at the sea-level gauges. Note though that statistical correlations can identify the relationship between physical variables, however this does not prove causation (Tsimplis, 1995).

The second part of the Chapter investigates the frequency and magnitude of storm surges at Moturiki, and whether they are influenced by the SOI. Weather conditions around New Zealand are known to be influenced by the SOI, and so therefore we can expect a correlation with storm surge. Storm surge at Moturiki was investigated due to the longest available sea-level record from April 1974 to the end of January 2018, and also for comparison with previous research (de Lange & Gibb, 2000; Goring, 2006). The frequency of annual storm surges was compared for a range of different thresholds. Storm surge frequency and maximum magnitude each month were also obtained to correlate with monthly SOI. The aim is to investigate whether the frequency and magnitude of storm surges have been increasing, and whether they are related to the SOI.

6.1 Atmospheric Pressure and Wind

Wind and atmospheric pressure data from Tauranga Airport were supplied by MetService for the period 1995 to 2016. Wind and atmospheric data from Totara St, Mount Maunganui, was also obtained from the BOPRC for the period 2006 to the end of January 2018. Pressure data were joined together, to create a total analysis period from 1995 to 2018 (Figure 6-1). This was correlated to storm surge data from the sea-level gauges to investigate how much storm surge variability is explained by atmospheric pressure.

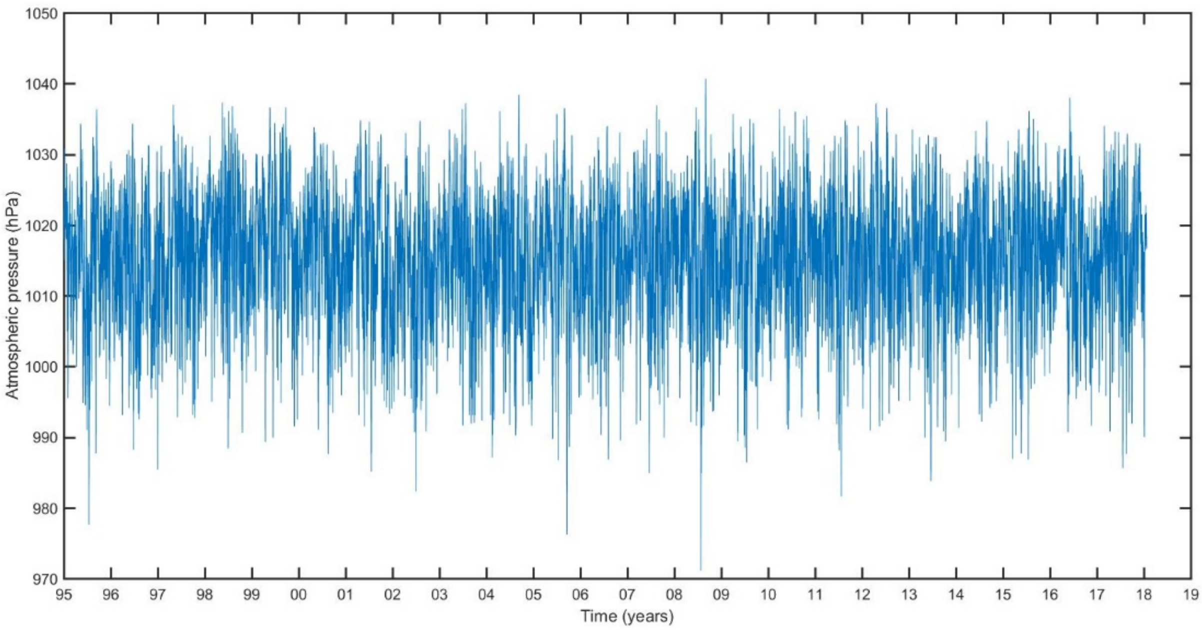

Figure 6-1 Joined atmospheric pressure from Tauranga airport (1995 to 2016), and Totara St (2017 to the end of January 2018).

Wind direction data from Totara St was joined to data from Tauranga Airport, to create a record that covered the period 1995 to 2018. Wind speed data at Totara St was significantly lower than at Tauranga Airport, and therefore a regression was carried out between the two sites for the overlapping period 2006 to 2016 (Figure 6-2) in order to provide a relationship to scale the data. The formula for the wind speed correction at Tauranga Airport is shown in equation 1.5:

$$\textbf{Tga\_corrected = 1.2123 * totara + 0.2601} \qquad (1.5)$$

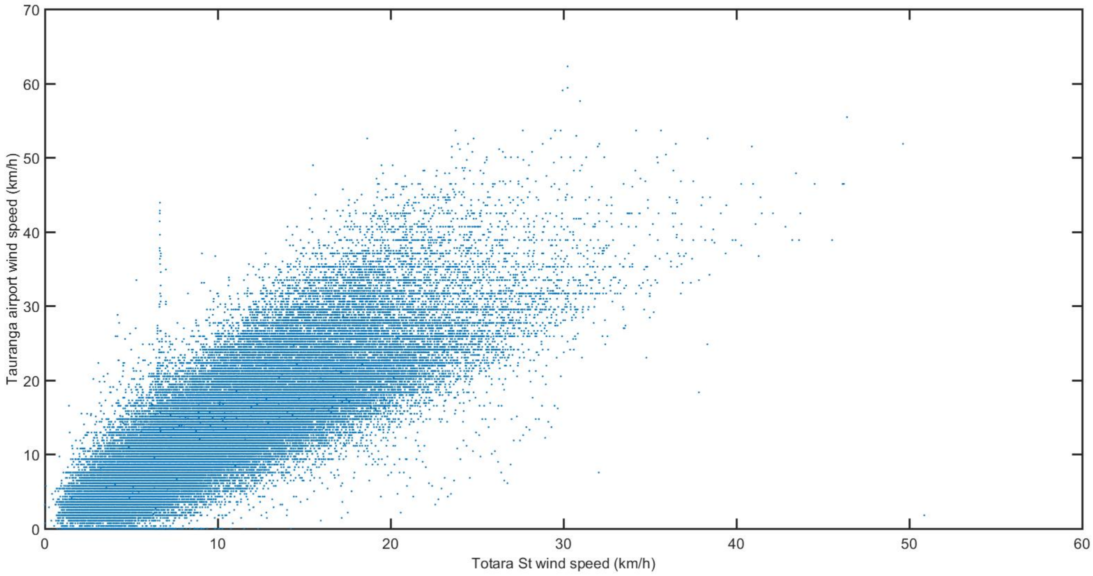

Figure 6-2 Wind speed at Totara St, plotted against Tauranga airport for the overlapping period 2006 to 2016.

This enabled wind speed data for 2016 to 2018 to be estimated for Tauranga Airport. The new corrected segment of data was joined to the existing time series to complete the record from 1995 to 2018 (Figure 6-3).

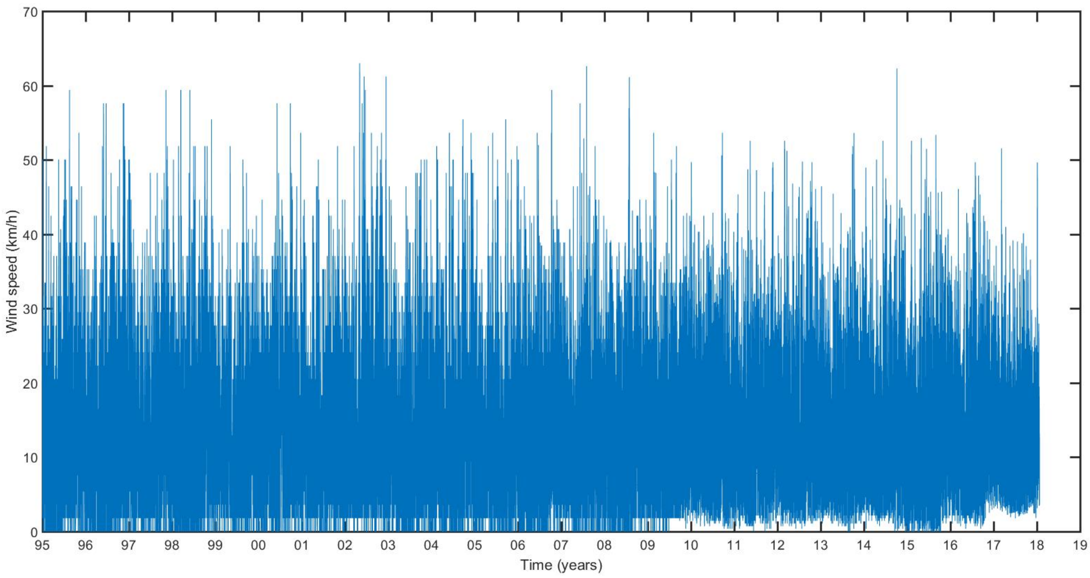

Figure 6-3 Corrected wind speed for Tauranga Airport for the period 1995 to the end of January 2018.

6.1.1 Stepwise Regression

Regression analysis aims to determine how much of the variability of one variable can be explained by the variation of another or several other variables. This was carried out using the built in stepwise regression software in MatLab to determine how much of the variance in storm surge is explained by atmospheric pressure and wind. The analysis consists of fitting a regression model that contained multiple variables, with the ability to add or subtract them from the model to determine whether the prediction of the independent variable improved substantially. The significance of the regression model is based on the F-test, with higher F values corresponding to a stronger model. The model is considered to be statistically significant when the p value is less than or equal to 0.05. The r^2 regression parameter is used to measure the amount of storm surge variance that can be explained by atmospheric pressure and wind. I considered a successful model to be one in which values of r^2 are 0.4 and above. The wind variables included the u_north component (wind from the north), and the v_east component (wind from the east).

6.1.2 Results

Atmospheric pressure alone was found to explain 37% to 49% of storm surge variability, depending on the location of sea-level gauges. This is supported by highest F values being associated with the model between storm surge and pressure. Wind was found to explain small levels of storm surge variability, with the largest influence being from wind blowing from the east, which explains an extra 3% to 15% of storm surge variability in addition to atmospheric pressure. Atmospheric pressure alone was shown to account for 49% of the variance in storm surges at Tug Berth (Table 6-1). When the u_north component was included, the variance stayed at 49%, however including the v_east component resulted in 55% of the variance in storm surge being explained.

Table 6-1 Stepwise regression for pressure and wind on storm surges at Tug Berth.

Regression parameters	Pressure	Wind (u_north)	Wind (v_east)
r^2	0.49	0.49	0.55
F	176651	88580	111835
Slope	-0.005	0.0007	0.005
Intercept	0	5.5	6.1

Atmospheric pressure alone was shown to account for 47% of the variance in storm surges at Moturiki (Table 6-2). When the u_north component was included the variance stayed at 47%, however with the v_east component included 53% of the variance in storm surge was explained. Therefore storm surges at Moturiki are explained slightly by wind from the east. This can be explained by the winds from the east causing a set-up in sea-level along areas of the western BOP, such as Tauranga Harbour.

Table 6-2 Stepwise regression for pressure and wind on storm surges at Moturiki.

Regression parameters	Pressure	Wind (u_north)	Wind (v_east)
r^2	0.47	0.47	0.53
F	181347	90682	114987
Slope	-0.005	-0.0001	0.004
Intercept	0	5.16	5.72

Atmospheric pressure alone was shown to account for 44% of the variance in storm surges at Hairini (Table 6-3). When the u_north component was included the variance increased to 45%. Therefore storm surge at Hairini can be explained slightly by winds coming from the north. When the v_east component was included, 53% of the variance in storm surge was explained. Therefore storm surges at Hairini are explained most by winds from the east. This aligns with the location of the gauge which is located on the Hairini Bridge, being exposed more to fetches from the east coming from the Oruamatua basin.

Table 6-3 Stepwise regression for pressure and wind on storm surges at Hairini.

Regression parameters	Pressure	Wind (u_north)	Wind (v_east)
r^2	0.44	0.45	0.53
F	109830	57685	78013
Slope	-0.005	-0.0001	0.004
Intercept	0	5.16	5.72

Atmospheric pressure alone was shown to account for 37% of the variance in storm surges at Omokoroa (Table 6-4). When the u_north component was included the variance increased slightly to 38%. When the v_east component was included instead, 52% of the variance in storm surge was explained. This is the most significant increase in storm surge variance explained by wind. The Omokoroa gauge is located on the eastern side of the Peninsula, and is exposed to largest fetches from the east to west from the southern entrance.

Table 6-4 Stepwise regression for pressure and wind on storm surges at Omokoroa.

Regression parameters	Pressure	Wind (u_north)	Wind (v_east)
r^2	0.37	0.38	0.52
F	88166	45548	79964
Slope	-0.005	0.002	0.008
Intercept	0	5.02	6.07

Atmospheric pressure alone was shown to account for 48% of the variance in storm surges at Oruamatua (Table 6-5). When the u_north component was added, there was no significant increase. When the v_east wind component was added, 51% of the variance in storm surges was explained.

Table 6-5 Stepwise regression for pressure and wind on storm surges at Oruamatua.

Regression parameters	Pressure	Wind (u_north)	Wind (v_east)
r^2	0.48	0.48	0.51
F	126617	63739	71600
Slope	-0.006	-0.001	0.004
Intercept	0	6.12	6.63

6.2 Discussion

6.2.1 Atmospheric Pressure and Wind

Atmospheric pressure alone was shown to explain 37% to 49% of the variance in storm surges at the sea-level gauges. Goring (2006) found atmospheric pressure explains roughly 50% of storm surge variability at Moturiki (47% found in this study) however did not apply the regression to sea-level gauges inside Tauranga Harbour due to shorter patchy records. The slight difference between studies is likely the result of different data sources and periods being used, along with regression methods. Atmospheric data from Rotorua Aerodrome was used due to the longer data record overlapping with Moturiki for the period 1974 to 2005. In comparison this study used atmospheric and pressure data from Tauranga Airport, covering the period from 1995 to 2018.

Goring (2006) also applied a cross correlation which found storm surge leads atmospheric pressure by approximately 3 hours at Moturiki. This is consistent with findings of Goring (1995) which found that at northern sites in new Zealand, sea-level changes approximately 3 to 4 hours prior to changes in atmospheric pressure (however this may be different for specific events). Atmospheric pressure generally explains low levels of sea-level variability, which is supported by this study. The response of sea-level was less than the theoretical IB of + 1 cm for every 1 hPa drop in pressure. This could be expected as there is generally always some variation around the theoretical IB, often due to trapped waves and friction (Goring, 1995). The structure and bathymetry of the coastal environment within enclosed waters can also violate the theoretical IB (Tsimplis, 1995). Goring (1995) reported regional wind stress was not found to be correlated with sea-level and concluded that wave propagation is likely to explain the remaining sea-level variability.

With respect to wind, wind from the east was found to have the most influence on storm surge, explaining an extra 3% to 15% of the variability. The influence from wind is largest at Omokoroa. This is not surprising as the largest fetch occurs from the east to west in the southern basin. The Omokoroa gauge is exposed to this being located on the eastern side of the Peninsula, with the largest fetch compared to other sea-level gauges. Tug Berth is not exposed to wind fetches blowing from the east even though this had the most influence on storm surge variability. Instead, sea-level at Tug Berth may be influenced more by sea-levels along the open coast. In Tauranga a positive storm surge can arise from a low pressure system accompanied by onshore winds (easterly) or longshore wind up the coast to the left (de Lange & Gibb, 2000). As a result sea-levels around Tauranga can become temporarily raised which could be influencing sea-levels at Tug Berth. In comparison, during periods of offshore winds (west to south-west) sea-levels in Tauranga Harbour fall slightly, and pile up down the coast along the eastern Bay of Plenty around East Cape. The remaining variance in storm surges is likely influenced by waves propagating into Tauranga Harbour, along with meteorological forcing (Goring, 2006). Storm surge variance can be explained by processes that influence atmospheric pressure, wind stress, sea-surface temperature and salinity over varied time periods (Pugh, 1987).

6.3 Frequency and magnitude of storm surge at Moturiki

Storm surge frequency and magnitude at Moturiki were analysed using purpose built MatLab software. Annual storm surge frequency at Moturiki are summarised using histograms for a range of thresholds, >0.1 m, >0.2 m, and >0.4 m (Figure 6-4). The 0.1 m threshold was used by de Lange and Gibb (2000) along with Goring (2006) and has been used in this Chapter for consistency and comparison. Independent storm surge events were identified as being more than 48 hours apart. The main findings show:

- Storm surges exceeding 0.1 m occurred between 3 to 25 times per year, with an average of 19 per year. A total of 820 events were identified.
- Storm surges exceeding 0.2 m occurred between 0 to 6 times per year, with a total of 135 events identified.
- Storm surges exceeding 0.4 m were rarer, occurring between 0 to 3 times per year, with a total of 16 events identified.
- There is no evident change in the frequency of annual storm surge events at both the 0.1 m and 0.2 m thresholds.

- In recent years (since around 2012) there was a greater frequency of storm surges which exceeded 0.4 m.

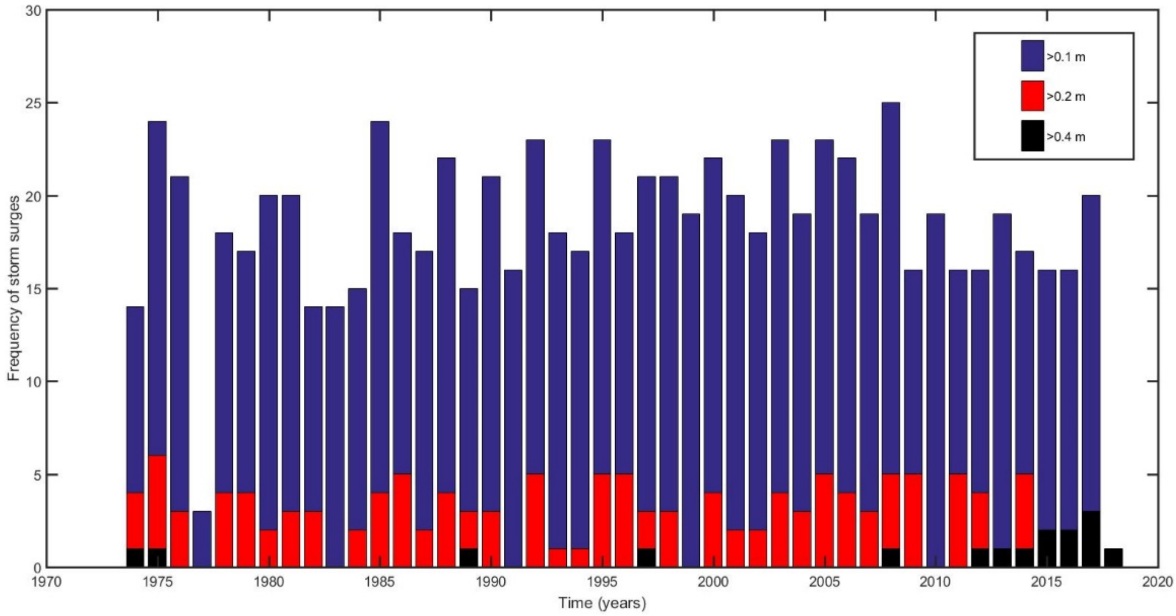

Figure 6-4 Annual frequency of storm surges exceeding three different thresholds (0.1 m, 0.2 m, 0.4 m) at Moturiki.

Storm surge frequency exceeding 0.1 m were plotted for each month based on the entire Moturiki record (Figure 6-5). Storm surges were found to be more frequent during Winter months, particularly June, July and August.

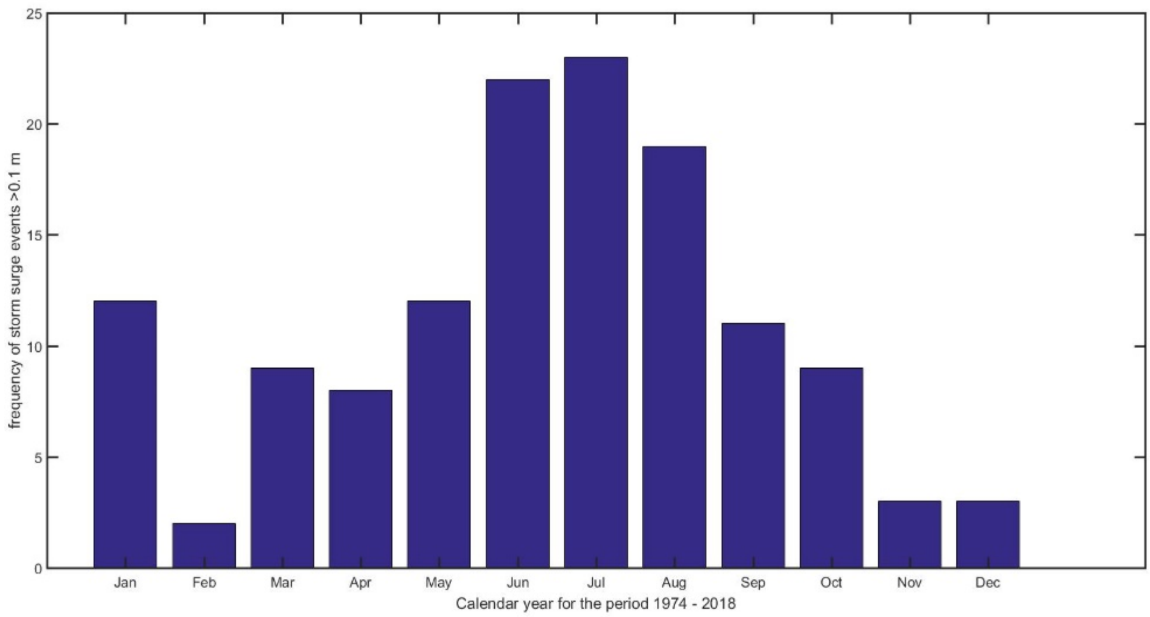

Figure 6-5 Frequency of storm surges per month, exceeding 0.1 m (for the entire Moturiki sea-level record, 1974 - 2018).

From the Moturiki sea-level record, approximately 25 years correspond to El Niño, and 18.5 years to La Niña conditions. With respect to these periods, 485 storm surges (exceeding 0.1 m) occurred during El Niño, and 408 during La Niña. When comparing storm surges for an equal time period (18.5 years for both phases) 374 occurred during El Niño and 408 in La Niña. This shows that in general, storm surges are more frequent during La Niña phases of ENSO. Based on the maximum monthly magnitude of storm surges, the average value for El Niño and La Niña years are 0.17 m and 0.19 m.

6.3.1 Storm Surge and the Southern Oscillation Index

Storm surge frequency and magnitude was investigated based on their relationship to the SOI. Monthly values of the SOI was obtained from the National Oceanographic and Atmospheric Administration (NOAA). The frequency and magnitude of monthly storm surges (above 0.1 m) are plotted against monthly SOI, and are summarized using a boxplots (Figure 6-6 and 6-8). The results between storm surge frequency and SOI were not found to be statistically significant. There is some indication that a lower frequency of storm surge events per month is likely to occur during weak El Niño phase of the SOI (negative value). This is shown as when the frequency of surges is zero, the median value has a slightly negative SOI. Storm surge frequency per month is higher during the weaker La Niña (positive value). This is shown as when the frequency of surges per month is higher, the median value has a slightly positive SOI.

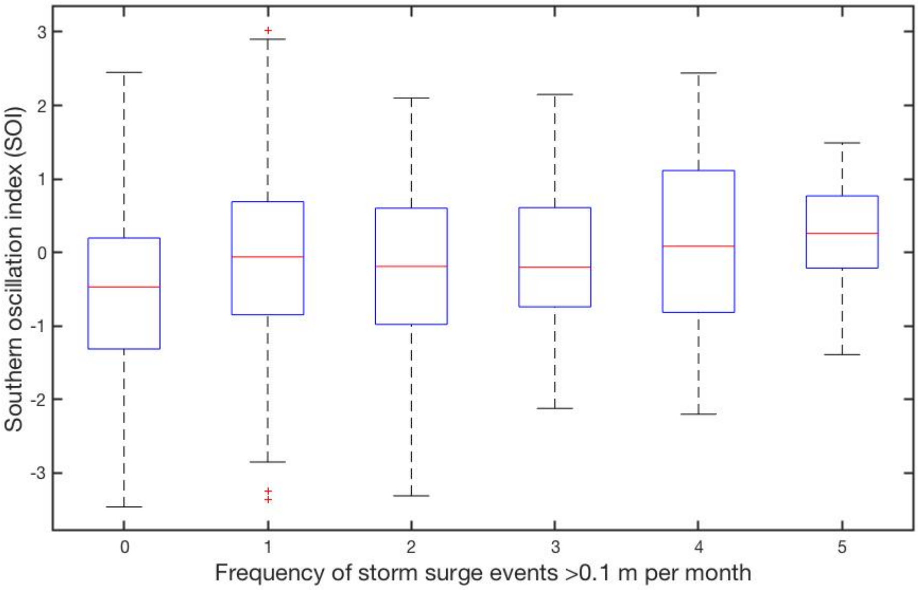

Figure 6-6 Frequency of storm surge events exceeding 0.1 m per month, plotted against monthly SOI. Each box contains 50% of the data, with the red line representing the median value. The dotted lines extending from each box show the minimum and maximum values.

The results between monthly maximum storm surge (>0.1 m) and SOI were not found to be statistically significant (Figure 6-7). A slight relationship is evident which shows storm surges of larger magnitude are more frequent during La Niña.

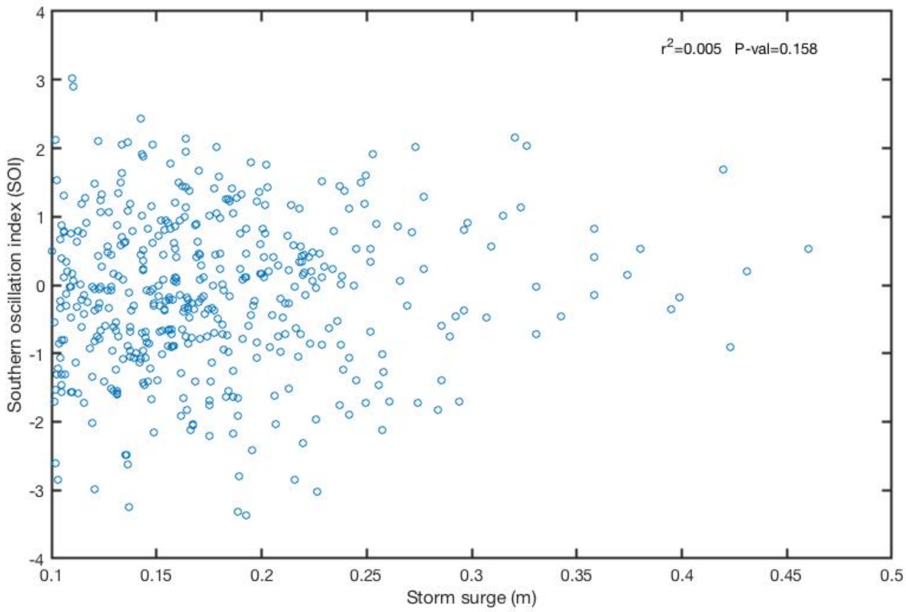

Figure 6-7 Maximum monthly storm surge at Moturiki, plotted against SOI.

A boxplot was used to show the relationship between maximum monthly storm surges and the SOI (Figure 6-8). In comparison smaller storm surges appear to be more frequent during weak El Niño phases of ENSO, however the range in SOI is larger.

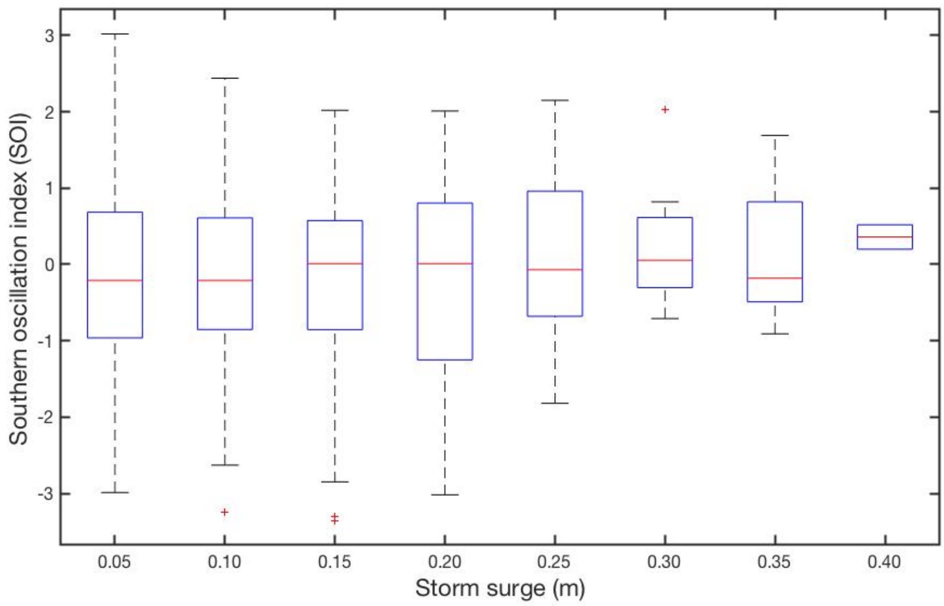

Figure 6-8 Boxplot of maximum monthly storm surge at Moturiki, plotted against SOI. Each box contains 50% of the data, with the red line representing the median value. The dotted lines extending from each box show the minimum and maximum values.

6.4 Discussion:

6.4.1 Storm Surge dependence on the Southern Oscillation Index

No significant changes were observed in the frequency of annual storm surges exceeding both the 0.1 m and 0.2 m threshold at Moturiki. A higher frequency of annual storm surges exceeding 0.4 m occurred since around 2012. The frequency of storm surges exceeding 0.1 m ranged from 3 to 25 per year, with an average of 19. This aligns with previous work by Goring (2006) which also used thresholds, finding the frequency was between 12 to 23 per year, with an average of 19. Goring (2006) reported no changes in the frequency of surges between 1975 and 2005. This contrasts results by de Lange & Gibb (2000) which analysed tide gauge data between 1960 to mid 1988.

de Lange & Gibb (2000) reported storm surge magnitude and frequency were greater during 1960 to 1976, but then significantly reduced from 1976 to 1988 which was suggested to be a response to changes in the IPO (20 to 30 year cycle). Storm surge was also reported to be influenced by ENSO with more frequent events during La Niña (2 to 4 year cycle). The response of storm surge magnitude and frequency to the IPO was predicted to be greater in the next few decades (i.e. present day) similar to previous IPO states such as those identified between 1960 and 1976. This is due to a shift in the IPO in the North Pacific (Salinger & Mullan, 1999) which will also influence the South Pacific from teleconnections. Therefore the higher frequency of storm surges exceeding 0.4 m in recent years could be the result of increased storm surge hazard that occurs during the IPO.

Discrepancies between the results of de Lange & Gibb (2000), Goring (2006) and this study are likely due to differences in methods used to extract storm surge and the time series periods used. de Lange & Gibb (2000) identified surges by looking at residual water levels between predicted high tide and recorded levels (Mount Maunganui and Tauranga tide gauges). Residual levels were analysed every 12.4 hours (every high tide) with surges being recorded if the sea-level was 0.1 m or more above the predicted water level. This differs to the method used by Goring (2006) and this study, which obtained continuous storm surge following extraction from the NTR. Longer period variations in sea-level (>1 month) were likely present in de Lange & Gibb (2000) compared to Goring (2006) and this study which removed MSLA from storm surge.

Storm surges were found to be influenced by seasonal changes. Surges exceeding 0.1 m are more frequent in winter months, particularly June, July and August. de Lange & Gibb (2000) found similar results with peak occurrences during March and August. They found storm surge magnitude was also largest from around March to July. The peak values around March could be explained by the tropical cyclone season in the south-west Pacific which is associated with more intense wind storms which track down towards New Zealand.

No statistically significant relationship was found between storm surge frequency and magnitude with the SOI. de Lange & Gibb (2000) also reported no significant relationship between storm surge magnitude and the SOI, however they did find that storm surges are more frequent during La Niña. Storm surges are slightly more frequent during La Niña (52%) compared to El Niño (48%), when comparing 18.5 years of data for each phase. An observable trend suggests both storm surge frequency and magnitude are greater during La Niña. This can be explained by increased atmospheric flows from the north-east which can increase storminess in the BOP and temporarily raise the sea-level during La Niña conditions (Heath, 1979; Goring & Bell, 1999; de Lange & Gibb, 2000).

6.5 Summary of key points

- Atmospheric pressure alone explains 37% to 49% of storm surge variance depending on location of the sea-level gauges (Omokoroa is explained the least and Tug Berth is explained the most).
- With respect to wind, wind from the east has the most influence on storm surge which explains an additional 3% to 15% of storm surge variance. Wind has the most influence on storm surge at Omokoroa. This is expected because Omokoroa is exposed to largest fetches from the north which impact low lying land on the northern side of the Peninsula, and fetches from the east which impact the eastern side.
- Sea-level at Tug Berth is also influenced most by wind from the east, and therefore may be effected by sea-levels at the open coast which becomes temporarily raised during persistent easterly (onshore) winds.
- Storm surges are frequent, with 820 events exceeding 0.1 m at Moturiki between 1974 and 2018.
- No evident changes in the frequency of annual storm surges exceeding either 0.1 m or 0.2 m thresholds was detected.
- In recent years (since around 2012) there was a higher annual frequency of storm surge events which exceeded 0.4 m. This could be a response to the shift in IPO.

- On average there are 19 storm surge events each year that exceed 0.1 m at Moturiki.
- There is some evidence that during La Niña, storm surges are more frequent and greater in magnitude, however the results are not statistically significant.

Chapter Seven

General Discussion and Conclusion

7.1 Storm Surge Extreme Value Analysis

Storm surges in Tauranga Harbour are influenced by the morphology of the coastline. The extreme value analysis shows storm surges are largest at Omokoroa, a result which aligns with previous work (Gibb, 1997; Stephens, 2017). This reflects the local shape of the coastline, with the sea-level sensor on the north eastern side of the Peninsula (Omokoroa wharf) being exposed to largest fetches from the east to west from the southern entrance. Low-lying land on the northern side of the Peninsula is also exposed to large fetches inside the Harbour from the north, explaining how wave setup and run-up contributes to high sea-levels at Omokoroa. Oruamatua also has relatively large storm surges which are likely caused by reflection and amplification within the Oruamatua basin. The results from this study show storm surges are also large at Hairini, most likely due to the relatively long fetch from the north. Stephens (2017) reports Hairini having lower values due to dissipation as the surge propagates into the Waimapu estuary.

The extreme value analysis on sea-level data provides useful information for implementing coastal hazard zones. Multiple extreme value techniques have been applied to sea-level data in Tauranga Harbour, with results generally being consistent. Stephens (2017) reported a larger extreme storm surge distribution due to the inclusion of the three large historical storm surges (1936, 1954 and 1968) which were not captured on the gauged sea-level record used for this study.

7.2 Drivers of Storm Surges in Tauranga Harbour

Results from Chapter 6 shows that atmospheric pressure alone explains relatively low levels of storm surge variance in Tauranga Harbour, at approximately 50%. This aligns with previous work on sea-level variability around New Zealand and on storm surges in the BOP (Goring 1995; Goring 2006). Wind from the east was found to have the most significant positive effect on storm surges at all sea-level gauges, explaining an additional 3% to 15% of the variance in storm surge. This is lower in comparison with other studies such as Hsu (2013), which reported that variations in wind stress explained 91% of the variance in the storm surge produced by Hurricane Sandy in October 2012, with similar results for Hurricane Irene in 2011.

The remaining variance in storm surges is likely explained by waves propagating into the BOP region. This is supported by findings from the event on the 5th January 2018 (Chapter 5) which indicates external wave energy entered the Harbour, causing significant wave setup around the entrance. Evidence from the survey of local water levels indicates the highest sea-levels occurred at Pilot Bay and Sulphur Point. This shows how waves can have a significant influence on sea-level variability in Tauranga Harbour. The largest impact from waves in the BOP region occurs during swell directions from the north to north east. Thuy et al., (2016) studied the interaction of storm surge and waves with the tide along the central Vietnam coast. Their results show that the surge-wave interaction is crucial, with the wave dependent drag improving the accuracy of storm surge level by up to 30%.

During La Niña conditions the storm surge hazard is expected to increase in the BOP region. The results indicate that storm surges are more frequent and slightly greater in magnitude during La Niña, however no significant relationship was identified. During La Niña conditions the east coast of the North Island of New Zealand experiences a temporary rise in sea-level due to thermostatic effects and increased atmospheric flows from the north east (Goring & Bell, 1999). Therefore it is reasonable to assume Tauranga Harbour will experience variable storm surges associated with the varied strength and phase of ENSO. The largest historical storm surges in Tauranga Harbour are associated with tropical cyclones from the north to north east (Hay, 1991; de Lange & Gibb, 2000). Tropical cyclones have the ability to generate storm surges up to three times as large as those from mid-latitude depressions (Gibb, 1997). Storm surges in Tauranga Harbour vary due to the nature of storms and their track relative to New Zealand. Three category 4 tropical cyclones migrated over New Zealand in the last century, with two of these tracking relatively close to Tauranga Harbour on the 2nd February 1936 and 9th to 10th April 1968 (Gibb, 1997). Due to climate change and associated warming of the atmosphere and ocean, this could lead to a rise in the frequency and intensity of extreme events such as storms and tropical cyclones which will impact the BOP region along with the overall New Zealand coast.

Weather reports should be monitored closely to detect any potential low pressure systems which could coincide with king tide conditions, with the potential to cause coastal inundation of low-lying land (Stephens & Bell, 2015). Areas with low gradients are more vulnerable to inundation due to water being able to move inland. The event on the 5th January 2018 produced one of the largest recorded surges at multiple sea-level gauges, coinciding with a spring high tide of 1.04 m. The estimated return periods vary depending on location, with ARI of between 50 to 200 years. The nature of extreme sea-levels are influenced by the magnitude of low pressure systems and their track relative to Tauranga Harbour. The most significant storm surges are generated from systems travelling from the north to north east quadrant. Therefore more exposed coastlines that face approximately north (north west to north east), have been shown to experience higher sea-levels.

Sea-surface temperatures (SST) should also be considered due to potential effects on extreme sea-levels at the coast. Liao, Lu, Yan, Jiang, & Kidwell (2015) found that coastal SST around low to mid-latitudes, including the South Pacific, experienced a cooling trend following 1998, referred to as the hiatus. Their findings did indicate that half of the global coastlines experienced continued warming in the hiatus period. This cooling trend in the South Pacific could be related to the recent shift in the phase of the IPO and eastern tropical Pacific cooling. The relative changes in coastal SST are greater than the change in the average global SST, which has resulted in higher frequencies of extreme hot and cold days (Liao et al., 2015). This could also have implications on the generation and track of storms and tropical cyclones which impact New Zealand, with the potential for increased storm surge hazard.

7.3 Limitations

The most reliable extreme value analyses generally use more data over the longest possible time series. The accuracy of extreme value analyses are influenced by the quality of data used along with the length and sampling frequency (Bell & Stephens, n.d.). The three Council operated gauges (Omokoroa, Hairini and Oruamatua) have relatively short records, being operated for less than 20 years. Therefore these gauges do not cover the full range of tidal conditions experienced every 18.6 years (tidal epoch) which could influence extreme sea-level results (Goring et al., 2010; Masselink et al., 2011). The quality of sea-level data from the gauges used in this study are variable. This is expected as records require varying degrees of quality analysis based on the amount of erroneous data, instrument jamming/fouling, sensor drift and timing issues (Bell & Stephens, n.d.). Sea-level records are patchier inside Tauranga Harbour compared to the longer record at Moturiki which is more continuous. This study along with Stephens (2017) noted large fluctuations in the non-tidal residual (NTR) at Oruamatua over periods of a number of months (Figure 7-1).

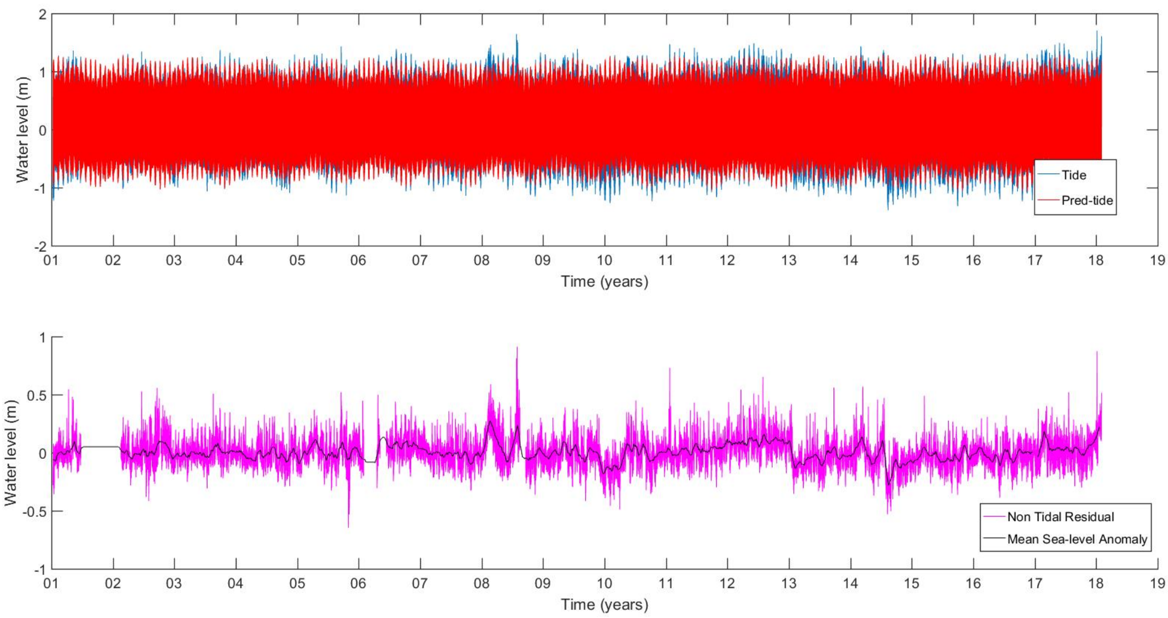

Figure 7-1 Oruamatua time series showing the measured tide, predicted tide, non-tidal residual (NTR) and mean sea-level anomaly (MSLA).

The high variability at Oruamatua could be explained by the interaction of wind with the morphology of Rangataua Bay including Welcome Bay (Oruamatua basin), however further research is needed. Oruamatua was shown to experience high sea-levels and storm surges, which could be the result of winds driving the water level up, with the constricted entrance trapping a large amount of water/energy. Tay et al., (2013) reports longer residence times in the upper parts of Tauranga Harbour, particularly in sub-estuaries with constricted entrances. Another potential reason for the high variability in the NTR could be due to sensor drift, since no datum reference checks were carried out. Stephens (2017) calculated the linear rate of SLR, showing that Tug Berth experiences rates higher than those expected from climate change. This indicates that the wharf pile on which the sensor is mounted to may be subsiding and should be re-surveyed (primary benchmark BC 84 code B309) (Stephens, 2017).

In addition to variable rates of relative sea-level change, archaeological evidence and crossing faults within Tauranga Harbour indicate that vertical land movements (VLM) are occurring (de Lange, Fox, & Moon, 2017). They suggest the two basins may be subsiding, with uplift along the ridge that separates them, which could explain partly why the Harbour displays low levels of infilling. Data from GeoNet are only short, operating since 2003; however they indicate that the eastern side of the Harbour experienced uplift until 2012 and has been subsiding since (de Lange et al., 2017). Further research and longer data records on VLM are necessary due to the variable effects from coastal hazards. Further study and increased understanding of VLM will facilitate work carried out on sea-levels and coastal hazards such as this study.

7.4 Future Research

7.4.1 Influence of Waves and Rainfall

Waves are suggested to explain the remaining variance in storm surges in Tauranga Harbour, however the effect of waves has not been quantified. Simulating Waves Nearshore (SWAN) is a powerful numerical wave transformation model, commonly used for investigating waves in shallow water for small scale site studies (Masselink et al., 2011). The numerical model can be applied to simulate wave propagation with high accuracy, given the boundary conditions are set appropriately. SWAN could be useful to determine the nature of waves in Tauranga Harbour, with the ability to respond to refraction, diffraction, currents and shoaling processes, along with predictions for storm surge run-up at the coast.

7.4.2 Mapping Areas Vulnerable to Inundation

Hydrodynamic models are useful tools which have the ability to simulate coastal processes such as storm surges. Models are an interpretation of reality and will only be useful if they can reproduce the outcome of reality with a high level of accuracy (Hearn, 2008). Due to the possibility of error in the measured/real values, a rigorous analysis of the available data is necessary before calibration takes place. NIWA has carried out work using a calibrated model to simulate tides, storm surges and waves which were used to define extreme sea-levels around the Auckland Region. This information was also applied to carry out coastal inundation mapping in a geographical information system (GIS) which used extreme sea-level data along with a digital elevation model (topography) obtained from Light detection and ranging (LiDAR) (Stephens & bell, 2015). The GIS modelling mapped areas of land which fell under the extreme sea-levels as inundated polygons (Figure 7-2).

Figure 7-2 Left: Aerial photograph of Mission Bay; Right: with present day 1% AEP storm tide plus wave setup elevation superimposed (purple shading), plus 1 m SLR (light shading), and plus 2 m SLR (orange shading) (Stephens & Bell, 2015).

This approach to flooding is known as the bathtub model, where all areas below the specified level are defined as inundated. In reality this level of flooding might not be realistic as the extreme sea levels from storm tides usually last between 1 to 3 hours during high tide and therefore flooding of some large areas might not occur to the extent shown by the model (Stephens & Bell, 2015). Therefore this modelling approach can over-predict inundation in some areas and should only be used for precautionary coastal planning. In some areas such as close to the shoreline, the model may also under predict due to the dynamic wave set-up, seiching and surging of infragravity waves (Bell et al., 2006). The bathtub model is applied best in regions were the topography rises at a constant rate with distance from the coastline, and should not be used in areas with sharp coastal barriers protecting larger low lying areas.

The Waikato regional Council (WRC) carried out similar mapping using GIS to identify areas that are vulnerable to coastal inundation from tides, storm surges and particularly SLR. WRC provided the online coastal inundation tool on their website in May 2016 with a strong positive response. This is a tool for public engagement and awareness on coastal hazards such as SLR, with the aim for the tool to be advanced and incorporated into a broader online hazards portal. Similar work using models and GIS mapping should be applied in Tauranga Harbour, which can be linked with the King Tides Project.

7.4.3 The Impact of Freshwater Input on Storm Surges and Sea-levels

Storm surge and inundation can be enhanced in large estuaries due to additional freshwater inputs (Garzon & Ferreira, 2016). Tropical cyclones experienced in the BOP region are generally accompanied by storm surge and high rainfall. This can enhance inundation and amplify storm surge around areas where significant freshwater input discharges into Tauranga Harbour. The largest freshwater input comes from the Wairoa River which drains the Kaimai Ranges and discharges into the Matua estuary with a mean flow of 17.6 m^3/s (Park, 2004). The Kopurererua and Waimapu Streams are also considerable. This study did not investigate the effects of high rainfall and freshwater input on the amplification of sea-levels across Tauranga Harbour. This is a potential area for future research.

7.4.4 King Tides Project

Present day king tides will likely be experienced more frequently in the future due to SLR and predicted increases in the drivers of coastal hazards. The term king tide was recognised around 2009 in Australia, with King Tides Projects spreading globally since (Roma´n-Rivera & Ellis, 2018). They are useful tools to engage the public with information around sea-levels and coastal hazards with increased pressure for coastal management and adaptation. The king Tides Project has already been set up in the Auckland region by the Auckland Regional Council, with the aim of it being set up in in the BOP region. Work from this study can be put toward the King Tides Project, including photographic evidence. Roma´n-Rivera & Ellis, (2018) highlight the need to define what a king tide is, suggesting they are higher than usual tides resulting from spring tides and atmospheric disturbances (low-pressure system or ENSO influence). Their impacts are variable, with the main issue of inundation causing damage to property and infrastructure however, with potential for harm to human life. Crowd sourced data and photographic evidence provide information on historical sea-level conditions. This data can build up over time and be used toward coastal planning, management and adaptation to climate change.

7.5 Overall Conclusion

One of the primary research aims was to understand how storm conditions amplify the sea-level in the Harbour. The POT extreme value technique was applied to sea-level data from five gauges, showing the largest storm surges occur at Omokoroa, and the smallest at Moturiki on the open coast. The variability of storm surges and extreme sea-levels in Tauranga Harbour are the result of multiple factors including the magnitude of atmospheric systems and their track relative to Tauranga, along with the response of the coastline physiography to these conditions. Additional methods such as oral histories and photographic evidence are necessary to validate estimated return periods, particularly due to short sea-level records. Atmospheric pressure alone explains low levels of storm surge variance. Wind from the east was found to have a significant influence on positive storm surges, which is explained by water piling up in the western BOP region following prolonged periods of onshore wind. Waves likely explain the remaining variance, which is supported by findings from historical events. No statistically significant relationship was identified between storm surges and the SOI.

The event on the 5th January 2018 caused significant inundation around Tauranga Harbour, and is an important reminder to monitor weather conditions closely during periods of king tide conditions. The hazard from storm surges may be predicted to increase resulting from climate induced SLR, and predicted increases in the frequency of storms which migrate toward New Zealand. This could result in present day extreme sea-levels occurring more frequently and reaching higher levels in the future. Some questions to explore for future research include: to what extent to waves explain storm surge variance in Tauranga Harbour? What is the influence of freshwater input following high rainfall on sea-level and storm surges? What areas are vulnerable to inundation using GIS to map extreme sea-levels, which incorporate elevations from the tide, storm surges and superimposed SLR predictions? This could be implemented in Tauranga Harbour in conjunction with the King Tides Project which aims to be a tool for community engagement in sea-level related issues and coastal hazards. This will allow better adaptation to coastal hazards in the future.

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Appendices

Appendix 1 Sea-level Time Series and Plots

Tidal constituents for the sea-level gauges, and the time periods used

Oruamatua		Hairini		Omokoroa		Moturiki		Tug Berth	
2001 - 2018		2002 - 2018		2014 -2018		1974 - 2018		1989 - 2018	
'M2'	0.728	'M2'	0.70765	'M2'	0.718424	'M2'	0.730871	'M2'	0.7007
'N2'	0.14325	'N2'	0.138562	'N2'	0.145681	'N2'	0.155242	'N2'	0.1436
'S2'	0.086967	'S2'	0.083912	'S2'	0.083714	'S2'	0.09684	'S2'	0.0875
'K1'	0.053285	'K1'	0.051959	'SA'	0.053316	'K1'	0.054759	'K1'	0.0543
'SA'	0.048751	'M6'	0.050373	'K1'	0.052067	'SA'	0.042094	'SA'	0.0426
'M6'	0.044832	'SA'	0.047117	'L2'	0.044667	'NU2'	0.029911	'NU2'	0.0279
'M4'	0.036639	'L2'	0.032569	'M6'	0.030397	'K2'	0.022561	'L2'	0.022
'L2'	0.031407	'2MN6'	0.026647	'NU2'	0.027621	'MU2'	0.021796	'K2'	0.0204
'NU2'	0.027804	'NU2'	0.026518	'M4'	0.023782	'2N2'	0.01965	'M4'	0.0185
'2MN6'	0.023208	'M4'	0.025116	'MU2'	0.021252	'P1'	0.0168	'2N2'	0.0176
'MU2'	0.02136	'MU2'	0.020228	'K2'	0.019908	'L2'	0.015978	'MU2'	0.0173
'K2'	0.020785	'K2'	0.019975	'2MN6'	0.016809	'O1'	0.011975	'P1'	0.0169
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'2N2'	0.016277	'MM'	0.016488	'P1'	0.016387	'S1'	0.008162	'M6'	0.0115
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'MSF'	0.013914	'MSF'	0.013782	'O1'	0.012249	'SSA'	0.005211	'LDA2'	0.0076
'2MS6'	0.013725	'M8'	0.013388	'MN4'	0.00985	'M3'	0.005134	'S1'	0.0071
'O1'	0.012542	'O1'	0.01205	'MF'	0.009764	'LDA2'	0.005024	'MF'	0.0061
'M8'	0.011771	'LDA2'	0.011259	'MSF'	0.009328	'EPS2'	0.004789	'2MN6'	0.006
'LDA2'	0.01164	'MN4'	0.009913	'2MS6'	0.008769	'J1'	0.004348	'SSA'	0.0055
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'MS4'	0.00699	'2MK5'	0.00733	'H1'	0.006394	'OO1'	0.002595	'M3'	0.0044
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'RHO1'	0.000604	'ETA2'	0.000618	'SO1'	0.000584	'TAU1'	0.000386	'2SK5'	0.0004
'2SK5'	0.000533	'2Q1'	0.00054	'ETA2'	0.000527	'M8'	0.000375	'2Q1'	0.0004
'MSK6'	0.000503	'CHI1'	0.000513	'MSK6'	0.00038	'ETA2'	0.000364	'SK4'	0.0004
'CHI1'	0.000419	'S4'	0.000503	'SK4'	0.000356	'MK3'	0.000356	'CHI1'	0.0003
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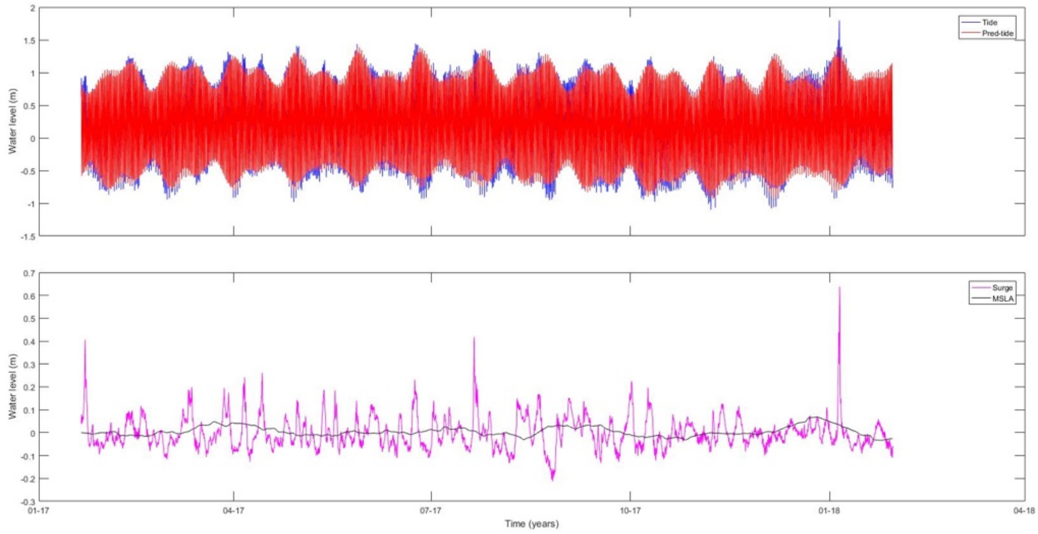
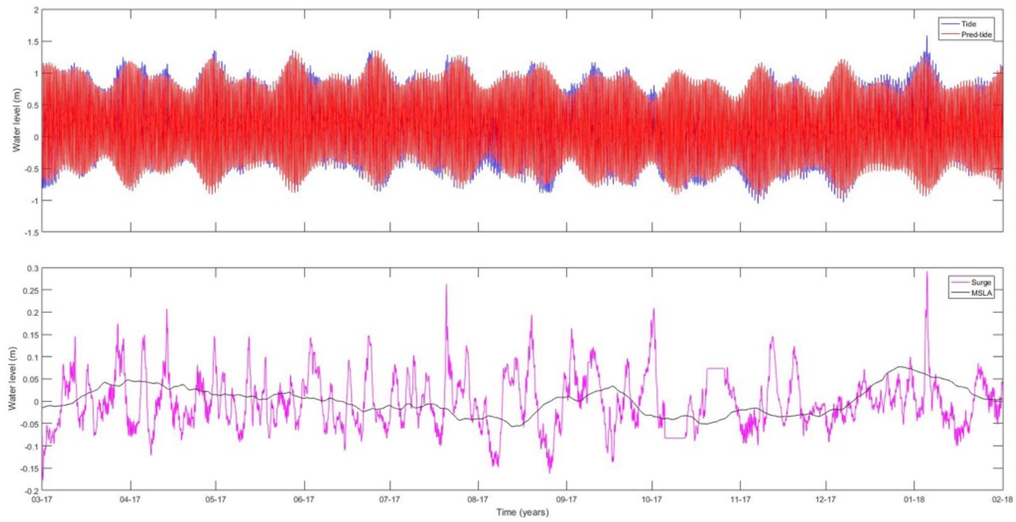
'ALP1'	0.00035	'ALP1'	0.00044	'CHI1'	0.00031	'MSK6'	0.000205	'MKS2'	0.0001
'BET1'	0.000296	'2SK5'	0.000363	'S4'	0.000283	'SN4'	0.000157	'2SM6'	0.0001
'SK4'	0.000282	'UPS1'	0.000353	'BET1'	0.000267	'3MK7'	0.000135	'BET1'	0.0001
'SIG1'	0.000276	'BET1'	0.000197	'RHO1'	0.000244	'BET1'	4.80E-05	'MSK6'	0.0001

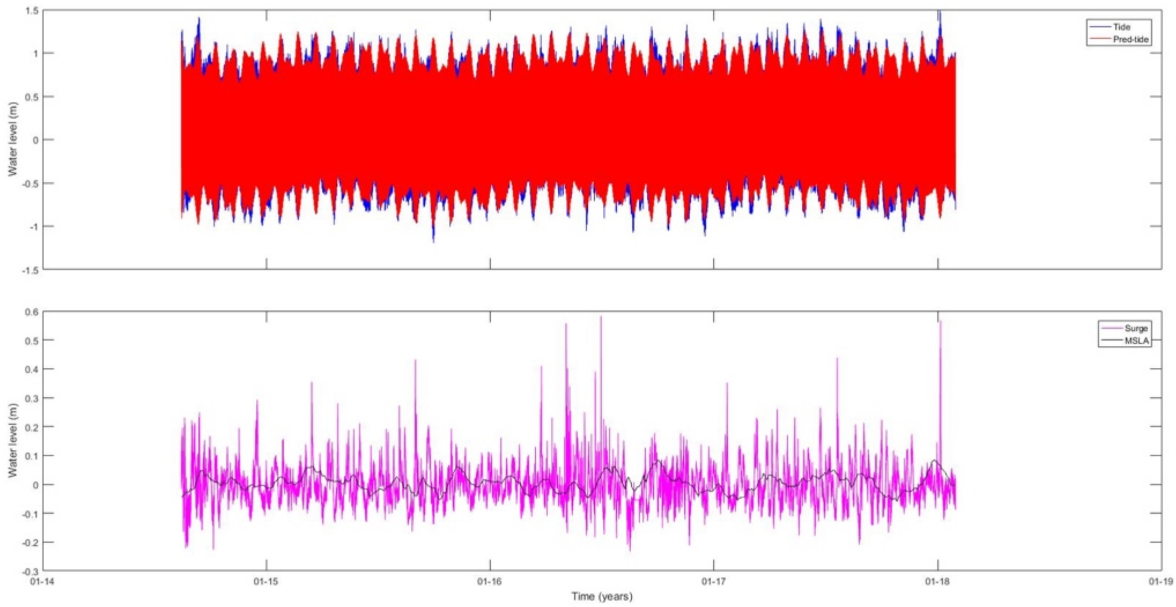
Plots of time series data for sea-level components



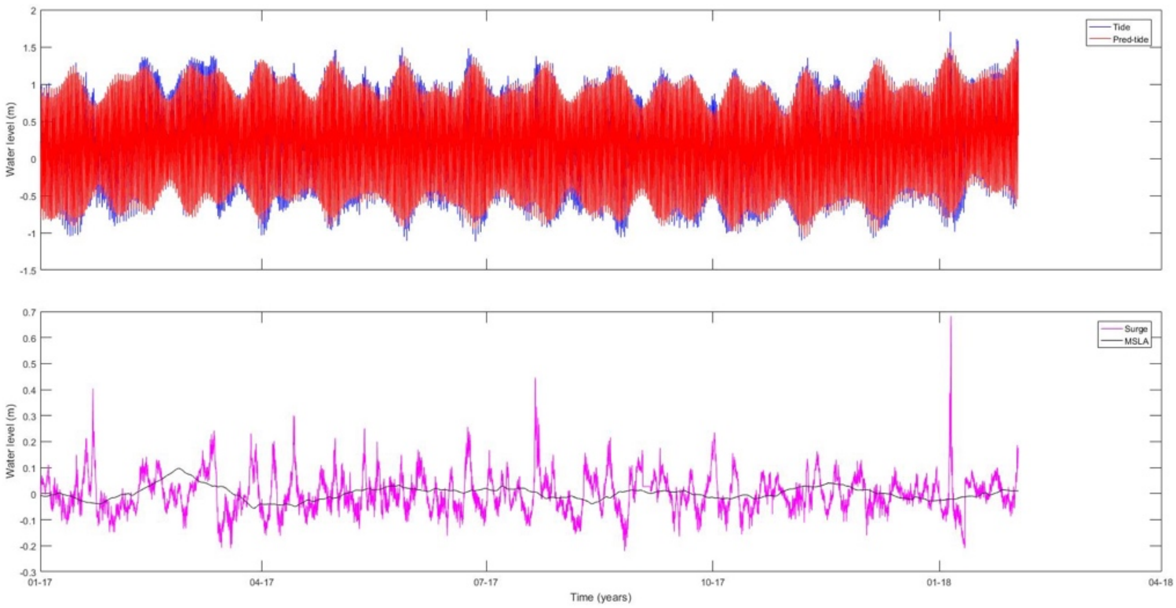
Hairini time series showing the recorded tide, predicted tide, surge and mean sea-level anomaly.



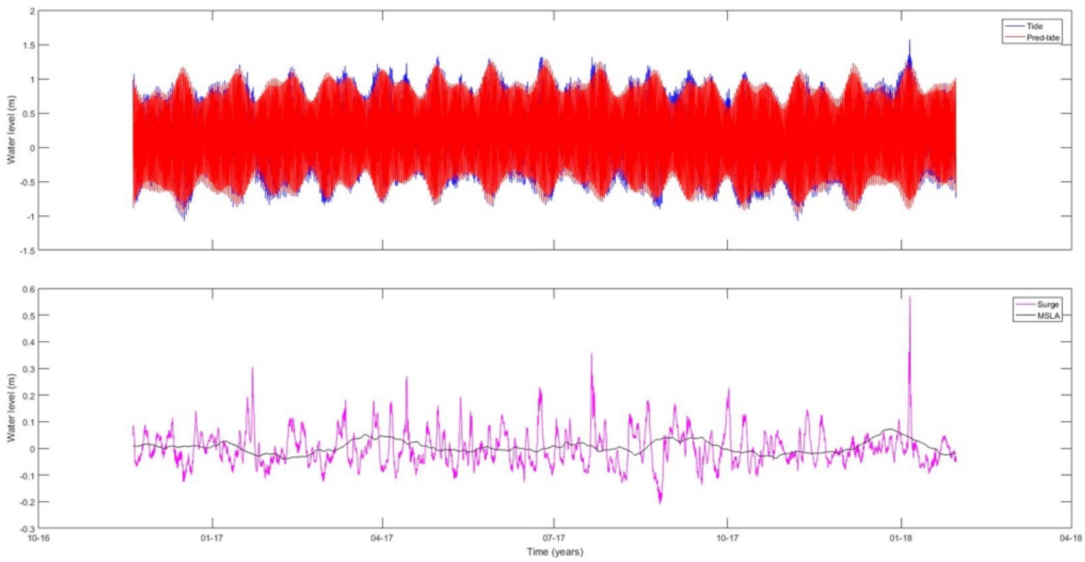
Moturiki time series showing the recorded tide, predicted tide, surge and mean sea-level anomaly.



Omokoroa time series showing the recorded tide, predicted tide, surge and mean sea-level anomaly.

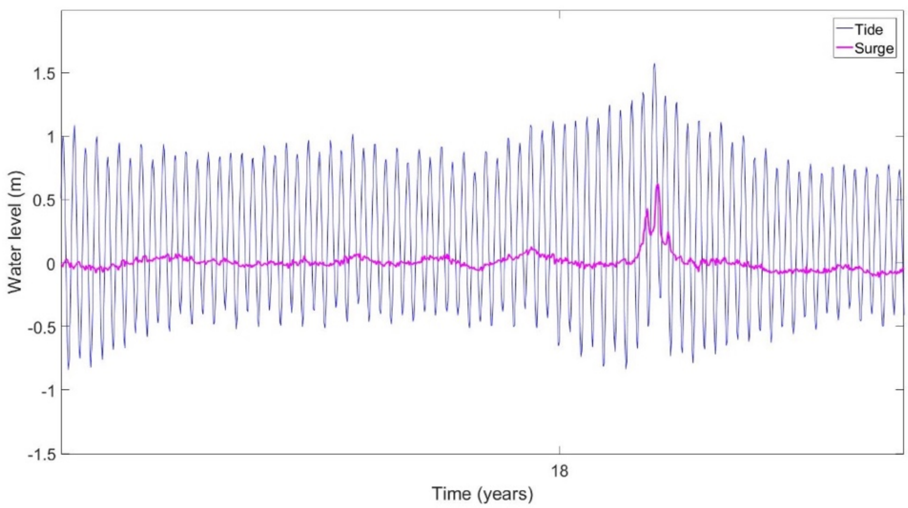


Oruamatua time series showing the recorded tide, predicted tide, surge and mean sea-level anomaly.

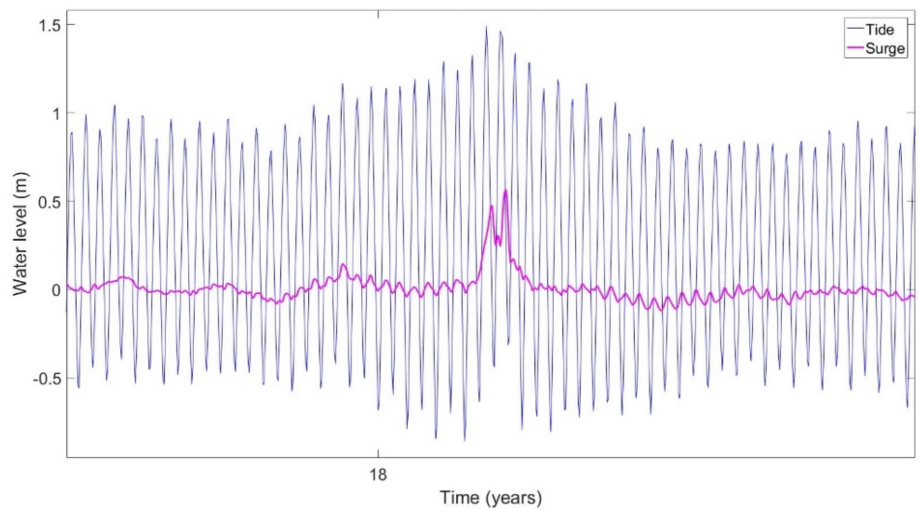


Tug Berth time series showing the recorded tide, predicted tide, surge and mean sea-level anomaly.

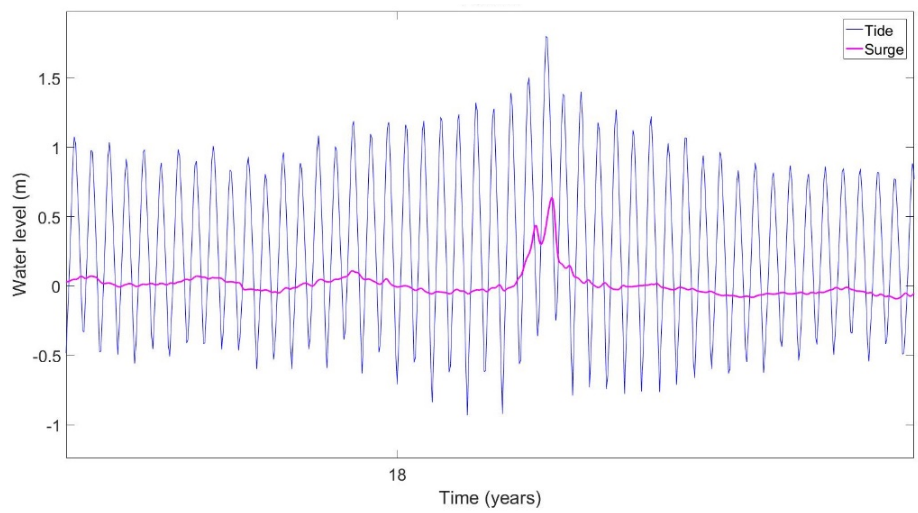
Plotting the tide and storm surge for 5th January 2018 event



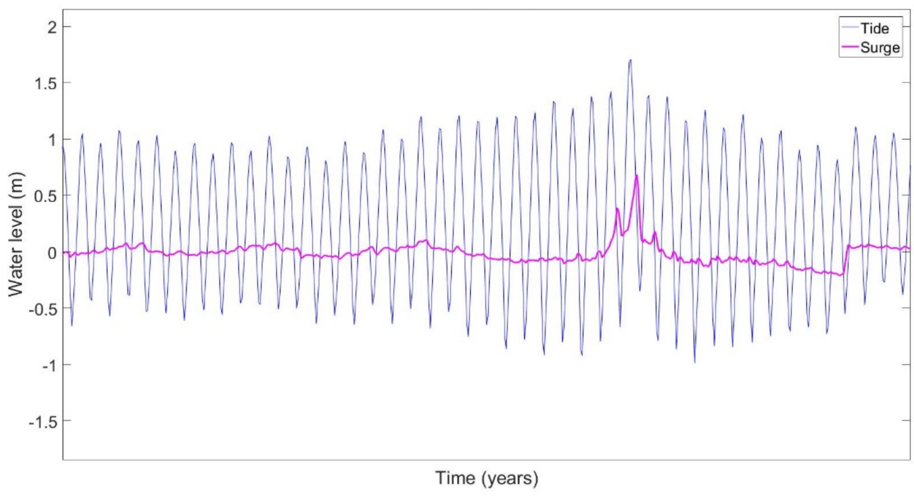
Recorded tide and storm surge at Tug Berth.



Recorded tide and storm surge at Omokoroa.

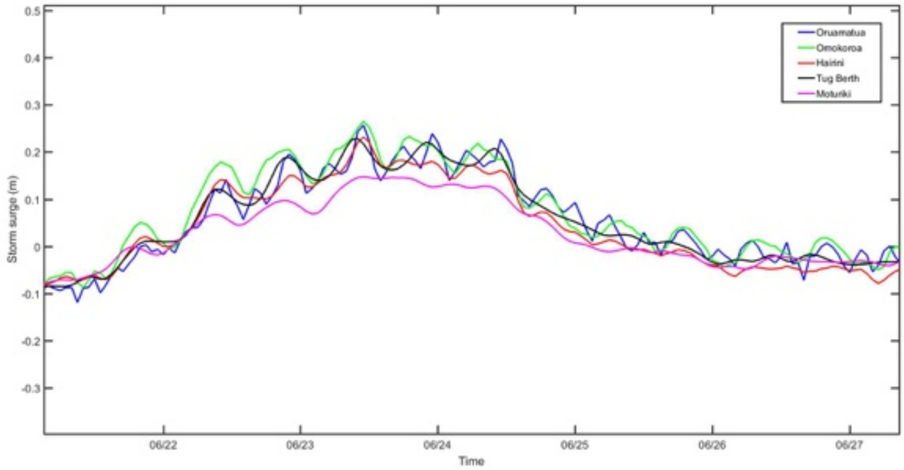


Recorded tide and storm surge at Hairini.

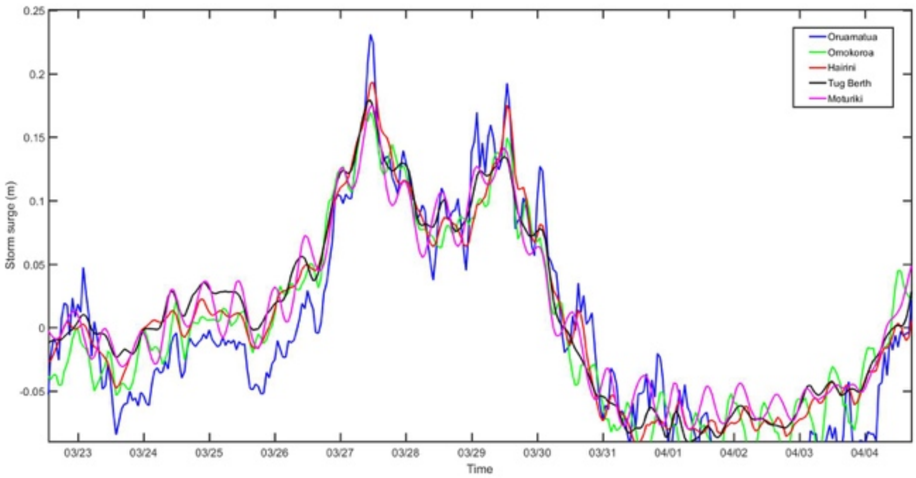


Recorded tide and storm surge at Oruamatua.

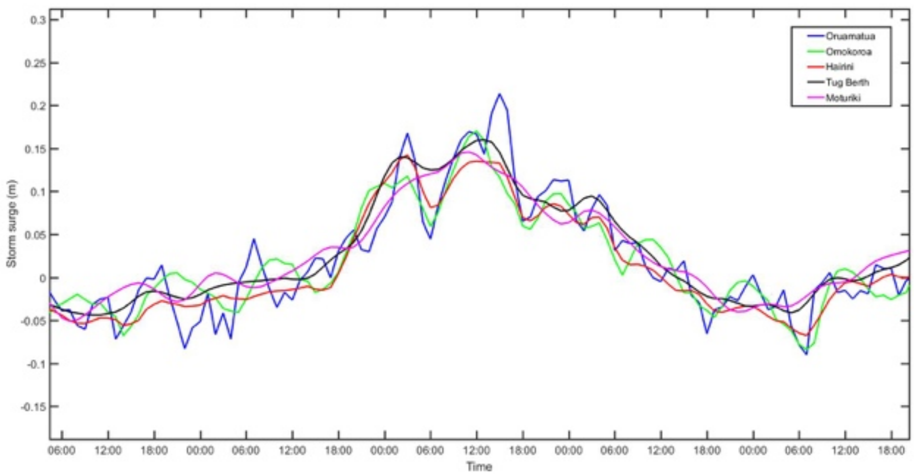
Storm surges extracted for the three photographed sea-level staff events



Storm surge event on the 24th June 2017.



Storm surge event on the 29th March 2017.



Storm surge event on the 30th April 2017.

Appendix 2 Research Ethics Approval

Dr Karsten Zegwaard

Chair, Human Ethics
Faculty of Science & Engineering
Te Pūtaiao me te Mātauranga Pūkaha
The University of Waikato
Private Bag 3105
Hamilton, New Zealand

Telephone 64-7-838 4892
Email k.zegwaard@waikato.ac.nz

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

To:	Mike Tyler
Date:	24-7-2017
From:	Dr Karsten Zegwaard
Subject:	Ethical approval for research
Application #	FSEN-2017-2

Dear Mike,

The Faculty of Science and Engineering Human Research ethics sub-committee has considered your proposal *"Storm tide propagation in Tauranga harbour".*

The proposal as attached is approved. If you wish to vary the terms of the approved application in any way, please contact me to request an amendment.

We wish you all the best with your research!

Signed ....

The University of Waikato

Application for Ethics Approval

Faculty of Science and Engineering

Human Research Ethics Sub-committee

1 Title of Project: Storm Tide Propagation in Tauranga Harbour

2 Researcher(s) and Contact Details

a Michael Tyler (1191097)

b FSEN School/Department/Centre/Unit

c 124a Ranch Road, Mount Maunganui, 3116

d Phone number: 021 02410706

e Past: BSc(Tech)
Current: MSc(Research)

g Other personnel
Supervisor: Karin Bryan (UOW)
Co-supervisors: Mark Ivamy (BoPRC) & Scott Stephens (NIWA)

3. Research Design Proposal

The committee needs to see some detail about your research design so it can judge if you have thought through all the ethical issues in your research. Describe your research design in points 3a-c below.

a. Research Objectives

The main aim of this research is to understand how storm conditions amplify the water level across Tauranga Harbour. The objective is to improve our understanding of the vulnerable areas, and verify these with existing data. This work is critical to council planning to allow adaptation to future climate change. The research also aims to set up the groundwork for implementing the King Tides project within the Harbour, following on from Auckland Council. The King Tides project is a tool to engage and inform the community about coastal inundation and sea-level rise, while providing crowd-sourced data for future hazard assessments.

b. Research Methodology

A detailed probability analysis will be carried out on water level recordings from council tide gauges at Te Puna and Rangataua Bay. Analyses of the water-level records will identify the separate roles of tide, storm surge and mean sea-level anomaly on extreme sea levels at the gauge locations. Due to short term water level records, predictions become harder to validate without the use of other methods. Techniques used by councils include using oral history and photographic evidence to fill in for missing long term records. Collaboration with the Bay of Plenty Regional Council (BOPRC) and NIWA will be an important component of the research. Discussions with estuary care groups and older people who have lived around the Harbour will aim to enhance our understanding of areas which might have inundated in the past, and therefore identify potential vulnerable areas for the future. Photographic evidence of important events (coastal inundation and erosion) will be added to the database and oral histories will aid in the verification of numerical model simulations. Another aim is to install water level poles in multiple locations around the Harbour that are determined as vulnerable to coastal inundation. These poles will allow for easy measurements and with photographic evidence, will provide strong information regarding extreme sea level events. Another component of the research will be to provide BoPRC the groundwork for setting up a 'KingTides' programme. This will be similar to Auckland Councils 'KingTides' programme, which is a community information and engagement tool with regard to coastal inundation, hazards and sea-level rise.

c. Significance of Research Project

The main objective is to enhance the understanding of areas around the Harbour that are vulnerable to coastal inundation. It is expected that this will be achieved, providing significant information which can be put toward coastal planning and management to allow adaptation to future climate change. Tauranga Harbour has been a focus area for scientific research; however, this will be the first study that aims to understand how storm conditions amplify the water level in the upper regions of the harbor, and therefore affect this hazardous zone. The research also aims to set up the groundwork for implementing the King Tides project within the Harbour, following on from Auckland Council.

Timetable of Events

Add dates where shown. You should allow three weeks to receive feedback on your ethics application.

Date	December 2016/ Jan 2017
Date	2017-June 2018
Date	2017-2018

4 Research Procedures

a Procedure for recruitment of participants

Participants will include landowners of properties which are located at the Tauranga Harbour-land boundary, specifically at low lying areas which are more vulnerable to coastal inundation. The Bay of Plenty Regional Council (BoPRC), will be assisting with contact details for participants who may be interested in this Research at these locations. Estuary care groups around the Harbour will also be a point of contact linked to the BoPRC. Local Iwi which are located at some of the low lying areas around the Harbour are another group which aim to be contacted, with Caine Taiapa having already been notified of the Research objectives (he is the main point of contact between Iwi and the BoPRC). In total there will be the estuary care groups, Iwi and multiple landowners (potentially 10+).

b Procedures in which research participants will be involved

Providing historical information such as photographs/dates for specific locations where an extreme water level (nuisance flooding), occurred. Another aim is to have some of the participants/landowners install a water level staff (wooden post with measurements on it) near the water level boundary. This will allow consistent locations for the landowners to be able to take photographs during extreme water levels and send them to a safe location/dropbox where both the BoPRC and myself can access them. This is because the research aims to set up the groundwork for the King Tides project around Tauranga Harbour, which is following on from Auckland Council.

c Procedures for handling information and materials produced in the course of the research

No hard data will be needed, and all electronic data will be kept on a password protected device. All data will be kept for a minimum of five years after collection before being destroyed, as national laws require this.

5 Ethical Concerns

a Access to participants

Contacts through the BoPRC. All contacts will be sent information regarding the research via email/phone, including their potential assistance/involvement. First contact/meetings can then be arranged at each location/property.

b Informed consent

Each participant will be contacted and notified of the proposed research (either email or phone). Their consent regarding any assistance/involvement will allow the next step to take place. My thesis proposal will be sent to the participants to give them further information (a hard copy can also be supplied). The participants will be asked about historic water levels, particularly identifying extreme water levels, with the aim of collecting photographic evidence of these events and also starting a new location for photographs to be taken (archive for the King Tides Programme - BoPRC). At these locations, water level staffs will be installed, with consent from participants.

c Confidentiality

All gathered data is based around high tide levels and the participant's observations and photographic evidence of these events. Their personal confidentiality is considered important as part of this research. The raw data of water levels will not be confidential. Any data on opinions from any source (e.g. Council decisions), will be confidential.

d Potential harm to participants

There will be minimal harm to the participants as their involvement will consist primarily of oral histories and photographic input from their own land. Participants will be able to view the data before it is used, to allow any corrections and/or removals to the supplied information. Note that flood risk hazard is an aspect included in property valuations.

e **Participants right to decline**

Participants have the right to decline their involvement in the research/study. Participants also have the right to withdraw at any time, without stating any reason or without impacting the person adversely..

f **Arrangements for participants to receive information**

As participants are contributing toward the research, it is fair to keep them informed about the study. This can be achieved through email/phone/meetings. The final information with regards to the research/thesis will be available.

g **Use of information**

Information obtained from participants aims to be used in the research/thesis, along with setting up the groundwork for the King Tides Project being setup by the BoPRC. It has been proposed that a 'dropbox' type system is used where crowd sourced data can be sent (from the multiple water level staffs which will be installed around the Harbour). The Research may also be presented at a conference. The research may also be used for future research publications.

h **Conflicts of interest**

No.

i **Cultural sensitivity**

Iwi consultation/participation in my research aims to benefit both parties and therefore minimal conflict should occur. The first point of contact will be through Caine Taiapa (BoPRC main Iwi contact), where my supervisors and myself can all go and meet the target Iwi groups/participants. The research will be undertaken with sensitivity to their cultural needs and follow traditions where appropriate.

j **Compensation for participation**

No.

k **Procedure for resolution of disputes**

Should any conflicts not be resolved firstly with the primary researcher, contact details for my supervisor (Karin Bryan) are given (see Appendix). And if this does not resolve the issue, the Dean of Science should be contacted.

6 Ethical Statement

The following statement must be included in your application and you are expected to be familiar with the Regulations of 2008 (see http://calendar.waikato.ac.nz/assessment/ethicalConduct.html)

The project will follow the University of Waikato Human Research Ethics Regulations 2008 and the ethical guidelines of the NZARE and include the following. Informed consent of participants will be obtained, without coercion. Exploitation (or perception of exploitation) of researcher-participant relationship will be prevented. Privacy and confidentiality will be respected. The participant will own the raw material collected, and their requests regarding the material will be honored. Participation in the research will not impact academically on the participants.

If your research involves schools or early childhood centres, you should also be familiar with the Guidelines in Appendix 4 (see http://www.waikato.ac.nz/research/unilink/ethics/human_ethics.shtml).

7 **Legal Issues**

a **Copyright**
Indicate here any steps that you may need to take to respect intellectual property and copyright as specified in the Regulations of 2008.

b **Ownership of materials produced**
Participants own their own raw data and the researcher owns the interpretation and analysis of data. In the event of a withdrawal by the participant, any data obtained from them will be returned and not used in the study, where possible.

c **Any other legal issues relevant to the research**
No

8 **Place in which the research will be conducted**
Landowners properties (including Iwi), and public/Council land around Tauranga Harbour. Primarily at low lying areas of land which are more vulnerable to nuisance coastal inundation.

9 **Has this application in whole or part previously been declined or approved by another ethics committee?**
No

10 **For research to be undertaken at other facilities under the control of another ethics committee, has an application also been made to that committee?**
N/A

11 **Further conditions**
In the event of this application being approved, the undersigned agrees to request approval from the FSEN Human Research Ethics sub-committee for any change subsequently proposed.

12 **Applicant Request for Approval of Ethics Application**

This should be signed by the applicant and their research supervisor only after receiving feedback from the committee after the first electronic submission, as per instructions on the front of this document.

As the applicant:
For the study described, I agree to follow the conditions as specified in this application

Signed ______________________

Date 24/07/17

(*if applicable*)
As the applicant's research supervisor:
I am aware of this study and the conditions under which it is proposed to be undertaken

Signed ______________________

Date 24-7-2017

The ethics application is approved

Signed on behalf of the Committee ______________________
(Chairperson of the Committee or their nominee)

Date 21-7-2017

Ethics: Participant Information letter

Project Title

Storm Tide Propagation in Tauranga Harbour

Researchers: Michael Tyler, University of Waikato

We would like to invite you to take part in research we are undertaking.

The main aim of this research is to enhance our understanding of how storm conditions (storm tides) amplify the water level across Tauranga Harbour. The objective is to improve our understanding of the vulnerable areas, and verify these with existing data. This work is critical to Council planning to allow adaptation to future climate change. The research also aims to set up the groundwork for implementing the King Tides project within the Harbour, following on from Auckland Council. The King Tides project is a tool to engage and inform the community about coastal inundation and sea-level rise, while providing crowd-sourced data for future hazard assessments.

What are participants required to do?

Information obtained from participants will be in the form of historical recollections of king tides/coastal inundation in Tauranga Harbour. Verbal accounts, photographic evidence and historic newspaper articles are all appropriate for the research.

What will happen to the information collected?

The collected de-identified data will be stored in the offices of the researchers in locked filing cabinets and password secured computers for duration of five (5) years from the completion of the research before being destroyed.

The data will be analyzed and may be presented at conferences or used for research publications. Participants can have access to stored data relating to them at any time by written request to the researcher. The participant owns the raw data, and the researcher owns the analyzed data. The raw data of water levels will not be confidential. Any data on opinions from any source (e.g. Council decisions) will be confidential.

Declaration to participants

If you take part in this study, you have the right to:

- Refuse to answer any particular question, and to withdraw from the study at any time without penalty or adverse consequence.
- Ask any further questions about the study before, during or after your participation.
- Be given access to a summary of findings from the study when it's concluded.
- Be ensured that the data be stored securely and destroyed five years after completion of the research.

Who is responsible?

This research has been approved by the Faculty of Science and Engineering Human Research Ethics Sub-committee of The University of Waikato. If you have any complaints or queries about the conduct of this research you are invited to contact firstly:

Dr Karsten Zegwaard, Cooperative Education Unit, University of Waikato, k.zegwaard@waikato.ac.nz

And then

Associate Professor Karin Bryan (Chief Supervisor)

University of Waikato.

P: +64 7 838 4123 E: k.bryanl@waikato.ac.nz

Appendix 3 Surveyed locations for the 5th January 2018 event

Site 1: Pahoia.

Site 2: Omokoroa golf course.

Site 3: Omokoroa domain.

Site 4: Waitui Reserve.

Site 5: Matua, south facing sheltered location.

Site 6: Wairoa River bridge.

Site 7: Ferguson Park (left), Site 8: Ferguson Park (right).

Site 9: Harbour Drive.

Site 10: Chapel St.

Site 11: Waikareau walkway on the north western side.

Site 12: Waikareau walkway on the southern side.

Site 13: Sulphur Point.

Site 14: Harbourside Restaurant on the Tauranga waterfront.

Site 15: Memorial Park, Tauranga.

Site 16: Grace Rd, Tauranga.

Site 17: Silver Birch Holiday Park, Waimapu estuary.

Site 18: Waimapu estuary, south east side.

Site 19: Hairini bridge.

Site 20: Maungatapu Marae, Maungatapu.

Site 21: Rotary Park, Maungatapu.

Site 22: Welcome Bay western site, moderately sheltered.

Site 23: Welcome Bay exposed site, Tye Park.

Site 24: Pilot Bay southern carpark.