Tauranga Harbour extreme sea level analysis

Prepared for Bay of Plenty Regional Council

August 2017

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NIWA CLIENT REPORT No: 2017035HN
Report date: August 2017
NIWA Project: BOP17202

Quality Assurance Statement		
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	Formatting checked by:	Alison Bartley
	Approved for release by:	Dr David Roper

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Executive summary

Bay of Plenty Regional Council (BOPRC) commissioned NIWA to analyse the sea-level gauges within the Tauranga Harbour, comparing them with the long-term NIWA gauge on Moturiki Island (open coast). The main purpose of the study was to provide extreme storm-tide parameters for calibration of hydrodynamic storm-inundation modelling of Tauranga Harbour, and to provide localised sea level rise parameters for Tauranga Harbour for future coastal-hazard studies.

BOPRC requested that NIWA provide:

1. Extreme sea level elevations resulting from storm-tides for at least the following three likelihoods at all five gauge locations within Tauranga Harbour:
   - 0.2% annual exceedance probability (AEP).
   - 1% AEP.
   - 2% AEP.
2. Define present mean sea level (i.e., 2020) for the Tauranga Harbour.
3. Define projected sea level rise (SLR) values for 50 years (i.e., 2070) and 110 years (i.e., 2130), including any positive or negative offset due to known ground movement.
4. A technical report clearly describing the methodology, results and any limitations.

Sea-level data was analysed from:

- Moturiki Island
- Tug Berth / Salisbury Wharf (Mount Maunganui),
- Sulphur Point / Tauranga (Slipway),
- Hairini Bridge
- Oruamatua
- Kotuku Reserve (Te Puna)
- Omokoroa Wharf.

Extreme sea levels were calculated inside Tauranga Harbour at each of the gauge sites, and are plotted in Figure 8-5 and presented in Table 8-6 relative to MVD–53 in the year 2020 (assuming recent rates of rise continue for next few years). For comparison, the maximum potential sea levels are shown in Table 8-5 (calculated using a “building block” technique, which combines maximal values of individual components).

The median (or “most likely”) 0.01 (1%) AEP extreme sea levels, relative to MVD–53 in 2020 were 1.87, 1.92, 2.14, 2.26, 2.17 and 1.88 m respectively at Mount Maunganui, Tauranga, Otumoetai, Omokoroa, Oruamatua and Hairini. The extreme sea-level outputs at Otumoetai and Omokoroa are reliant on large historical surge observations there, and although the analyses use the nearest sea-level gauge record, the analysis output location does not exactly match the gauge location.

Omokoroa and Otumoetai have the largest extreme sea levels reflecting the exposure to large wind fetches inside the Harbour at high tides, and the large historical surges observed there. Oruamatua also has large surges resulting from amplification of surge within the Oruamatua basin relative to Tauranga. Hairini has the lowest predicted extreme sea levels, reflecting the dissipation of both tides and surge into the Hairini basin.

The extreme sea-level analyses used the digital sea-level records, supplemented by eye-witness accounts of 3 exceptional storm-surge events that occurred during ex-tropical cyclones in 1936, 1954 and 1968, which are reported by Gibb (1997). These three surge events are clearly from a different, more extreme population of meteorological events than other measured surges (and likely included wave setup and possibly runup processes not measured by a tide gauge). I used a new best-practice extreme sea-level method, which has not been applied in New Zealand before, the skew-surge joint-probability method. The method allowed to incorporate the historical skew-surge estimates with the modern sea-level records, before combining with tides. The predictions of the most extreme sea levels are highly sensitive to the reliability of eye-witness accounts of the 1936, 1954 and 1968 surges. The results obtained were in close agreement with previous joint-probability results calculated by NIWA in 1997, but returned higher extreme sea levels than a study by T&T in 1999 which relied on maxima from measured data only.

The extreme sea-levels presented here do not include wave runup. Waves run up the beach much further than the average water level obtained from tide + surge. Wave runup is not responsible for substantial inundation beyond a few metres of the shoreline. I am uncertain how much the effects of wave runup influenced the eye-witness accounts of total water level. The largest observed total water levels occurred inland from the normal coastline, and therefore I have assumed for the extreme sea-level calculations that wave runup is a relatively small component on those observations. Should there be some runup effects then the results would be conservatively high in terms of widespread inundation, by about 0.3 m based on comparisons of sea-level gauges with wave-flotsam lines by Gibb (1997). Storm surge heights in estuaries can be significantly higher than on the open coast – reaching over 1 m – due to internal wind setup in harbour basins.

The main uncertainties in the extreme sea-level analyses result from: (i) a heavy reliance on historical eye-witness observations of 3 exceptional storm-surge events and the unknown wave influence on the historic observations, (ii) the mixing of sea-level gauge records from one site with historical surge observations from a different (nearby) site, and (iii) the extent to which bathymetric changes in the harbour since the 1980s would change the extreme sea-level analyses. Of these uncertainties, the first is the most influential, while the other two are of secondary influence. These uncertainties could in future be reduced by using numerical hydrodynamic models to relate tidal distributions from gauged sites to sites where historical surge estimates were collected, to test wind-surge and wave-setup generation inside the harbour, and to represent the modern harbour and its response to extreme sea-level events. Conversely, the extreme sea-level analyses estimate the likely frequency of occurrence of extreme sea-levels, so would be useful when designing modelling scenarios. A useful approach would be to use a hydrodynamic model to examine the response of the total water level in the harbour to various tide, wind and wave scenarios. These sensitivity tests can be put in context with the extreme sea-level analyses, and used to infer how the extreme sea-level analyses might be applied or adjusted spatially. Mean sea level (MSL) was calculated from the annual mean of the non-tidal residual (after subtracting the predicted tide). The Moturiki sea-level gauge provides a robust record for calculation of MSL and SLR trends, relative to Moturiki Vertical Datum 1953 (MVD–53). MSL at Moturiki was calculated for several epochs (Table 5-1), including the 1986−2005 epoch (mid-point 1995), which was used by the Intergovernmental Panel on Climate Change's AR5 assessment as the baseline mean sea level for future sea-level rise scenarios. MSL at Moturiki for a baseline period (1986−2005) was 0.07 m above MVD–53, and extrapolating the recent MSL trend to 2020 will be 0.13 m above MVD–53. MSL inside the harbour is 3–5 cm higher than at Moturiki, which is expected from the effect of friction exerted on tides moving through the harbour.

SLR projections were made for the Tauranga region for the years 2070 and 2130, relative to MVD–53 (Table 6-2). We selected four SLR scenarios, which are based around three greenhouse gas representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5). Three of the scenarios are derived from the median projections of global SLR for the RCPs presented by IPCC in their Fifth Assessment Report and extended out to 2130. The fourth higher ”H^+” scenario is at the upper-end of the "likely range" (i.e., 83rd-percentile) of the wide ensemble of SLR projections based on emission scenario RCP8.5. This H^+ scenario reflects the possibility of future surprises (deep uncertainty) towards the upper range in SLR projections of an RCP8.5 scenario. It is representative of a situation where more rapid rates of SLR could occur early next century from emerging polar ice sheet instabilities or as-yet uncertain understanding of dynamic ice sheet processes.

1 Introduction

In 2017, Bay of Plenty Regional Council (BOPRC) commissioned NIWA to analyse the sea-level gauges within the Tauranga Harbour. The main purpose of the study was to provide extreme storm-tide parameters for calibration of hydrodynamic modelling of Tauranga Harbour, and to provide localised sea level rise parameters for Tauranga Harbour for future coastal-hazard studies.

BOPRC requested that NIWA provide:

1. Extreme sea level elevations resulting from storm-tides for at least the following three likelihoods at all five gauge locations within Tauranga Harbour:
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2 Components and definitions of sea level

Before deriving extreme sea level, it is useful to first understand how different processes contribute to the most extreme sea levels. For example, historical observations might contain different sea-level contributions to modern sea-level gauge records. Sea-level gauges are usually located and designed to minimise the influence of waves and measure only the still-water level, whereas surveys of post-storm flotsam lines along the coast record the maximum wave runup elevation.

There are several meteorological and astronomical components contributing to sea-level variability (Figure 2-1). These coastal hazard sources can occasionally combine to cause coastal hazards that inundate low-lying coastal land, cause beach or cliff erosion, or drive changes in groundwater levels and salinity. The following sources of sea-level variability can combine to create coastal hazards, and I have <u>underlined</u> those which are relevant to this study.

- <u>Mean sea level (MSL)</u> – the average (mean) level of the sea, relative to a vertical datum over a defined period, usually of several years e.g., 19 years used by Land Information NZ for Standard Ports in their Nautical Almanac.
- <u>Mean sea-level anomaly (MSLA)</u> – the variation of the non-tidal sea level about the longer-term MSL on time scales ranging from a monthly basis to decades, due to climate variability. This includes the influence of El Niño Southern Oscillation (ENSO) and Inter-decadal Pacific Oscillation (IPO) patterns on sea level, winds and sea temperatures, and seasonal effects (see Factsheets).
- <u>High astronomical tides (high tide)</u>.
- <u>Storm surge</u> – the temporary increase in sea level, induced by winds and barometric pressure associated with weather systems.
- <u>Wave *setup* and *runup*</u> – wave *setup* is the temporary increase in mean still-water sea level at the coast, resulting from the release of wave energy in the surf zone as waves break. Wave *runup* is the maximum vertical extent of sporadic wave “up-rush” of flowing water (i.e., “green water”) on a beach or structure above the storm-tide level, and so is only a short-term upper-bound fluctuation in water level compared to wave *setup*.
- Wave overtopping – occurs when the wave *runup* exceeds the crest elevation of the beach or berm, and flows over (“overtops”) the top of the dune or seawall.
- Sea-level interaction with groundwater, including:
  - rising groundwater level
  - salinization of groundwater.
- Climate change effects, including:
  - changes in the storm surge and wave climate, e.g., increased storminess
  - <u>rising sea level</u> (incorporating both absolute and local contributors, e.g., vertical land movement).
- Vertical land movement from tectonic processes (earthquake event and inter-seismic periods) or sedimentary-basin subsidence.

- Tsunami from seabed ruptures during earthquakes, volcanoes or underwater landslides.

In addition to the individual sea-level components above, the following terms are relevant:

- Storm-tide is a combination of MSL (includes datum offset) + MSLA + high tide + storm surge (Figure 2-1). Storm-tide is a measure of the still-water elevation because it doesn't include wave-driven setup or runup. Storm-tide is measured by sea-level gauges.
- Total water level (TWL) is the total water level resulting from MSL (includes datum offset) + MSLA + high tide + storm surge + wave setup and runup. Gibb (1997) used the term *storm surge* to describe TWL. To minimise confusion, Gibb's definition is referred to as "*storm surge*$_{\text{(Gibb)}}$" henceforth.
- Storm surge can be determined or defined in different ways. The storm surge from definitions 1 and 2 below can be obtained from sea-level gauge records where wave effects are minimised:

  1. The difference between the measured total water level (TWL) and the predicted height of the closest high tide. This is also known as skew surge because the highest TWL can occur before or after high tide (skewed in time). The historical surge elevations reported by Gibb (1997) and those reported by de Lange and Gibb (2000) are measured in this way. The skew-surge joint-probability extreme sea-level method used in this study employs the same surge definition. Gibb (1997) used the notation *storm tide*$_{\text{(Gibb)}}$ to describe the skew surge.
  2. The difference between TWL and the predicted tide on an hourly basis, also known as the non-tidal residual. The revised joint-probability extreme sea-level method used by Goring et al. (1997) uses surge defined in this way.
  3. The historical *storm surge*$_{\text{(Gibb)}}$ captured by Gibb (1997) will include wave effects to some degree, but it is not possible to separate these out. However, I have used *storm surge*$_{\text{(Gibb)}}$ elevations collected inland where possible to try to eliminate wave runup effects from the estimates.

The different sources of data, and the different definitions of surge, can create difficulties when trying to account for historic information. For example, modern data collected by sea-level gauges provides reliable measurements of storm tide with a known accuracy. Surveyed elevations of eye-witness accounts of surge elevations (Gibb, 1997) have more uncertainties, such as whether they included substantial wave runup effects or not.

For example, for ex-tropical cyclones Fergus, Gavin and Drena, Gibb (1997) reports the *storm surge*$_{\text{(Gibb)}}$ obtained from the flotsam line left behind by wave runup. Waves run up the beach much further than the average water level obtained from tide + surge. In isolation, wave runup does not contribute substantial inundating volumes beyond several metres inland of the shoreline berm (compared to overtopping water levels comprising storm-tide and wave setup). Thus, the reported *storm surge*$_{\text{(Gibb)}}$ elevations may be above the elevations at which substantial inundation would be expected. For example, Gibb (1997) notes a difference of 0.3–0.35 m between the wave runup elevation (*storm surge*$_{\text{(Gibb)}}$) and the total sea level measured on the gauge, which is the storm-tide elevation in absence of wave effects (including wave setup).

This study uses historic surge elevations located inland of the coastline where possible, assuming that wave runup effects would be minimal there.

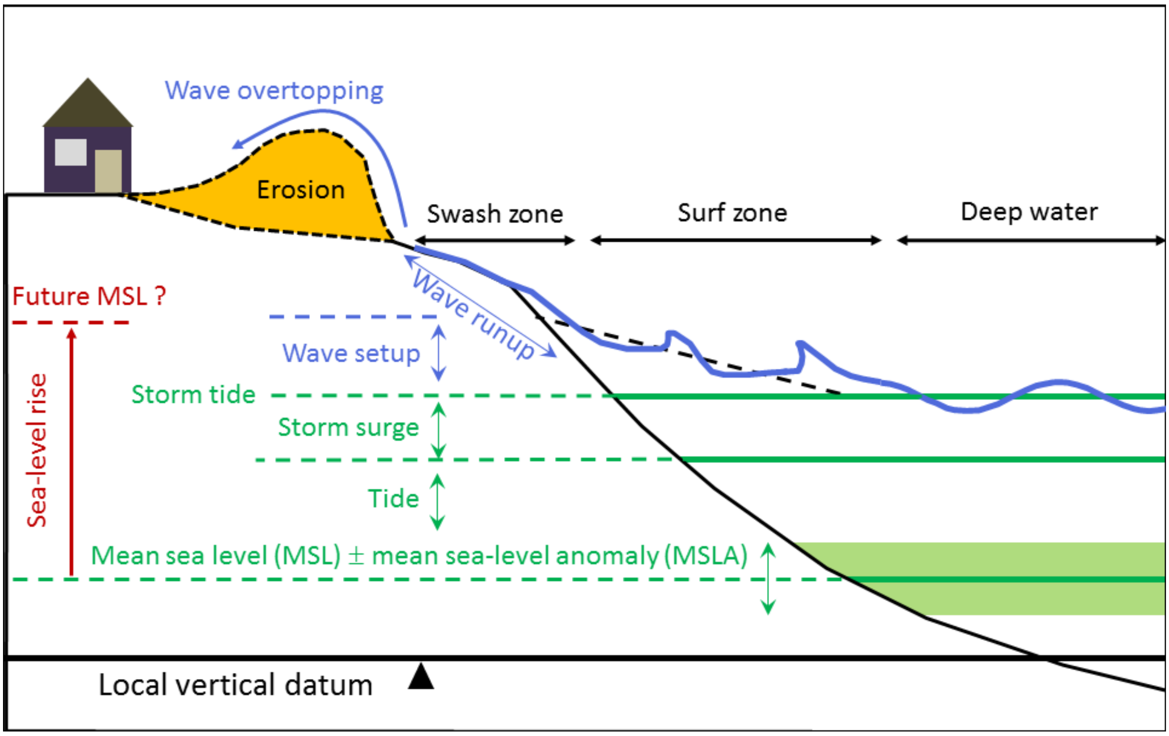

Figure 2-1: Coastal storm inundation and erosion sources.

3 Sea-level data

The digital sea-level data used for this study are described in Table 3-1. NIWA maintains the Moturiki sea-level gauge and supplied the data. Bay of Plenty Regional Council supplied sea-level data for the council-run gauges at Hairini Bridge, Oruamatua, Kotuku Reserve and Omokoroa Wharf. The Kotuku Reserve gauge was located at Plummers Point and operated from 2000–2013. The Omokoroa Wharf gauge was then installed nearby, but is of short duration so was not analysed in this study. Hourly data for the Tug Berth (Salisbury Wharf) was sourced from NIWA archives for 1989–2005, and data from 2005–2016 was obtained from the Port of Tauranga by Mike Tyler (a student sponsored by BOPRC). Dr Willem de Lange of the University of Waikato supplied high-water data from Sulphur Point from 1960–1998, which he used in previous research (de Lange & Gibb 2000).

Blackwood (1999) included historical annual maxima, digitised from paper sea-level charts. I have included this data in Table C-1, alongside annual maxima for Sulphur Point supplied by Dr Willem de Lange.

Historical storm-tide estimates from Gibb (1997) were also used, see Section 8.2, which used data from gauges located at both "Tauranga" and "Mount Maunganui".

Peter Blackwood (Blackwood 1999), in his Appendix to T&T's 1999 storm-tide report (T&T 1999), notes that "There seems to be some uncertainty about the location of this [Tauranga] site and the possibility that it may have shifted at some stage." Dr Willem de Lange remembers the location of some of the sea-level gauges. There was a gauge at Town (Tauranga) Wharf, also known as Coronation Pier. This gauge was later shifted to the slipway, which was filled in during construction of the harbour bridge. Dr de Lange suggests that the Mt Maunganui Wharf was almost certainly Salisbury Wharf. The tide gauge installed at Tug Berth moved around between different locations on the wharf initially. Another gauge was then installed 75 m up harbour from Salisbury Wharf at Tug Berth. It is evident from Table C-1 and Figure 3-2 that some of the data from the Sulphur Point record supplied by Dr de Lange is identical to that for the Tauranga gauge annual maxima from Blackwood (1999), which probably occurred as the Sulphur Point gauge replaced the original Tauranga gauge (Willem de Lange *pers. comm.*).

Table 3-1: Description of sea-level time series data used in this study. Hourly sea-level data from Sulphur Point were unable to be sourced for this study.

Gauge name	Easting (NZTM)	Northing (NZTM)	Record start	Record finish	Sampling frequency
Moturiki Island	1881145	5830405	1-Jun-74	28-Feb-17	Hourly
Tug Berth / Salisbury Wharf	1880670	5829265	1-Jun-89	20-Nov-16	Hourly
Hairini Bridge	1879000	5820870	5-Apr-02	20-Jan-17	Hourly
Oruamatua	1882454	5822671	10-Jan-01	20-Jan-17	Hourly
Kotuku Reserve	1868631	5827513	24-Nov-00	18-Aug-14	Hourly
Omokoroa Wharf	1869468	5830535	15-Aug-14	20-Jan-17	1 minute
Sulphur Point / Tauranga	1879684	5825008	16-Feb-60	17-Jul-98	High-water peaks

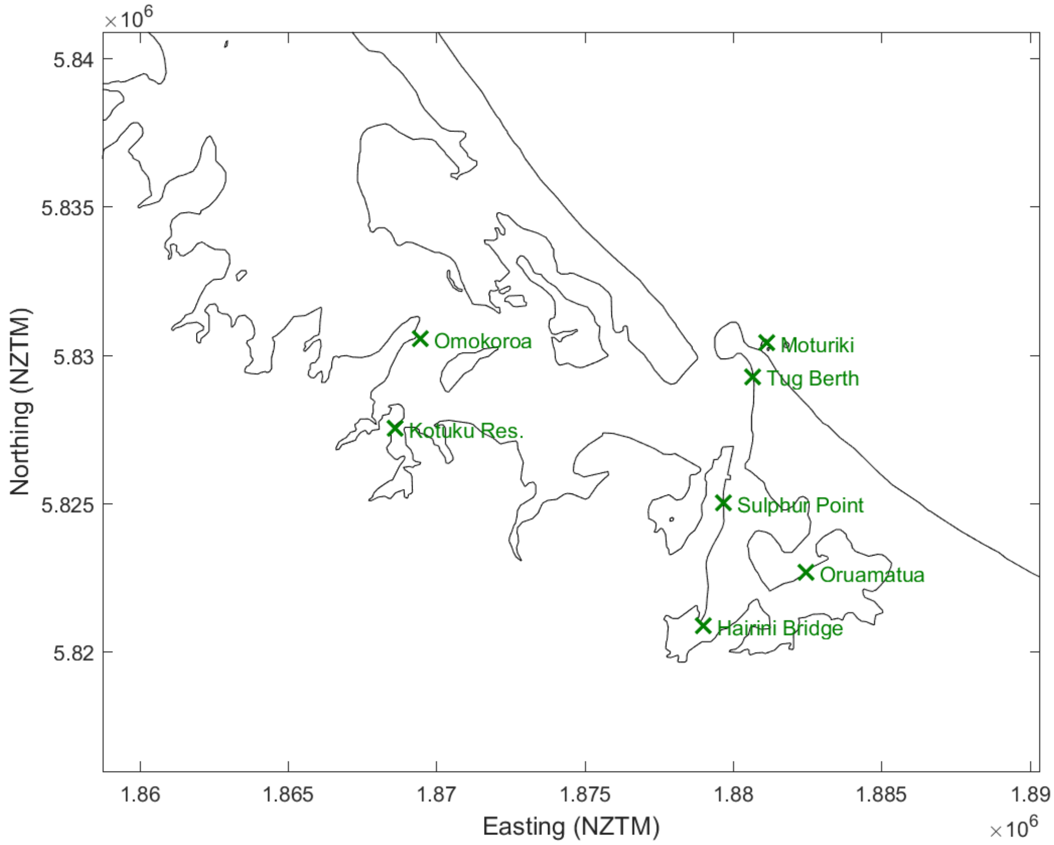

Figure 3-1: Sea level gauge locations.

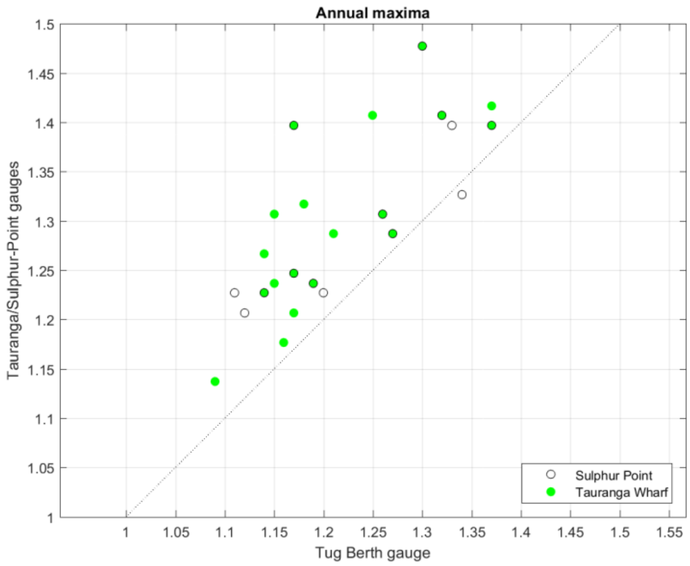

Figure 3-2: Scatter between matching annual sea-level maxima at Tug Berth and Sulphur Point / Tauranga.

4 Vertical datum

There are 4 datum's relevant to this study, defined as follows:

LVD (MVD–53) is the Local Vertical Datum, which is a fixed vertical survey datum for a specified region. Around New Zealand, these Local Vertical Datums were derived from the sea levels measured over several years, mostly during the 1910s to 1940s. For the Bay of Plenty region, the LVD is Moturiki Vertical Datum 1953 (MVD–53), which was derived from 4 years of sea-level measurements from Feb 1949 to Dec 1952 (Hannah & Bell 2012). Due to sea-level rise over the intervening period, the present mean sea level is usually several cm higher than the Local Vertical Datum (e.g., Table 5-1). Consequently, it is now confusing to call the LVD a Mean Sea Level (MSL) datum.

Gauge Zero is the zero datum of the sea-level recording instrument. Any data retrieved from the instrument are to this datum unless otherwise documented. 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).

NZVD2016[1] is the New Zealand Vertical Datum 2016 which is the official national vertical datum for New Zealand. NZVD2016 is defined by the NZGeoid2016 geoid. Heights in terms of NZVD2016 are in the normal-orthometric height system. The datum also defines relationship grids that enable heights to be consistently transformed from the 13 existing major LVD to NZVD2016. The values in the LVD relationship grids vary with horizontal position. NZVD2016 is formally defined in the LINZ standard LINZS25009 (Standard for New Zealand Vertical Datum 2016).

MSL is the actual Mean Sea Level averaged over periods of at least 1 month, but normally up to several years in reference to the prevailing slowly varying sea-level (obtained by a low-pass digital filter with a cut off period of 1 month). Storm surge, the tide and tsunami are often calculated in models relative to a pre-set MSL. MSL itself is a time-varying level that includes the effects of long period (>1 month) fluctuations in sea level, distinguished from the time-averaged MSL as sea-level anomaly (SLA). The SLA includes El Niño-Southern Oscillation (ENSO) effects and long-term sea-level change as well as seasonal variability. Storm surge, the tides, seiche, and long waves ride on top of the SLA at the time and are unaffected by it. MSL is typically expressed relative to a fixed vertical datum (i.e., LVD, gauge zero or NZVD2016). In some older NIWA reports the term "mean level of the sea" (MLOS) was used interchangeably with the term MSL.

The LINZ website provides conversions between MVD–53 and NZVD2016. Table 4-1 provides the calculated offsets at each of the gauge sites:

$H_{NZVD} = H_A - O_A$,

[1] http://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/vertical-datums/new-zealand-vertical-datum-2016-nzvd2016

where H_{NZVD} = the NZVD2016 normal–orthometric height in metres; H_A = the LVD *A* normal–orthometric height in metres; O_A = is the LVD *A* offset in metres evaluated from the relationship grid (MOT53–NZVD16) at the NZGD2000 position of the specific location.

Table 4-1: Offset between MVD53 and NZVD2016 datums at the sea-level gauge sites.

Gauge	Northing (NZTM)	Easting (NZTM)	O_A	MVD-53 (H_A)	NZVD2016 (H_{NZVD})
Moturiki Island	5830405	1881155	0.199	0	-0.199
Tug Berth / Salisbury W.	5829265	1880670	0.199	0	-0.199
Hairini Bridge	1879000	5820870	0.225	0	-0.225
Oruamatua	1882454	5822671	0.215	0	-0.215
Kotuku Reserve	5827513	1868631	0.243	0	-0.243
Omokoroa Wharf	5830535	1869468	0.243	0	-0.243
Sulphur Point / Tauranga	5825008	1879684	0.205	0	-0.205

5 Mean sea level

5.1 Mean sea level at Moturiki

The Moturiki sea-level gauge provides a high-quality and relatively long record which has been used to calculate annual MSL and long-term sea-level trends relative to MVD–53.

MSL was calculated from the annual mean of the non-tidal residual (after subtracting the predicted tide). Annual means were only calculated for years where the data record was at least 80% complete. The annual MSL data are presented in Table D-1. Figure 5-1 plots the annual MSL plus linear trend fits, and Table 5-1 presents MSL at Moturiki calculated for several epochs. The 1980−1999 epoch (mid-point 1990) was used by the Intergovernmental Panel on Climate Change's (IPCC) AR4 assessment (IPCC 2007) as the baseline mean sea level for future sea-level rise scenarios. The 1986−2005 epoch (mid-point 1995) was used by the IPCC AR5 assessment (Church et al. 2013) as the baseline mean sea level for future sea-level rise projections. The epoch 2000−2016 approximately spans the overlap with the gauges at Kotuku, Hairini and Oruamatua.

The rate of sea-level rise at Moturiki was 2.1 mm/year, calculated from a linear fit to annual MSL over the 42 years from the start of 1975 and the end of 2016 (Figure 5-1). By extending the linear sea-level rise trend, MSL at Moturiki is extrapolated to be 0.13 m MVD-53 by 2020, and 0.15 m by 2030. The linear rate of sea-level rise calculated for the 2000–2016 period is similar to but slightly higher than the 1975–2016 rate, being 2.9 mm/year. Hannah and Bell (2012) calculated a lower historic "inferred" sea-level rise rate of 1.9 mm/year at Moturiki, based on calculating a MSL datum for the 10-year period 1999–2008 inclusive, and comparing that baseline to the Moturiki Vertical Datum established in 1953 from sea-level data from 1949–1952. I performed the same calculation, obtaining a rise of 0.10 m over 53.5 years, which matches the 1.9 mm/year calculated by (Hannah & Bell 2012). Thus, the more recent rate of sea-level rise is higher (due mainly to climate variability in the Pacific from the IPO shift in 1999 but also from atmospheric and ocean warming). That rate is projected to accelerate in future due to global warming and associated impacts on oceans, glaciers and polar ice sheets (Section 6).

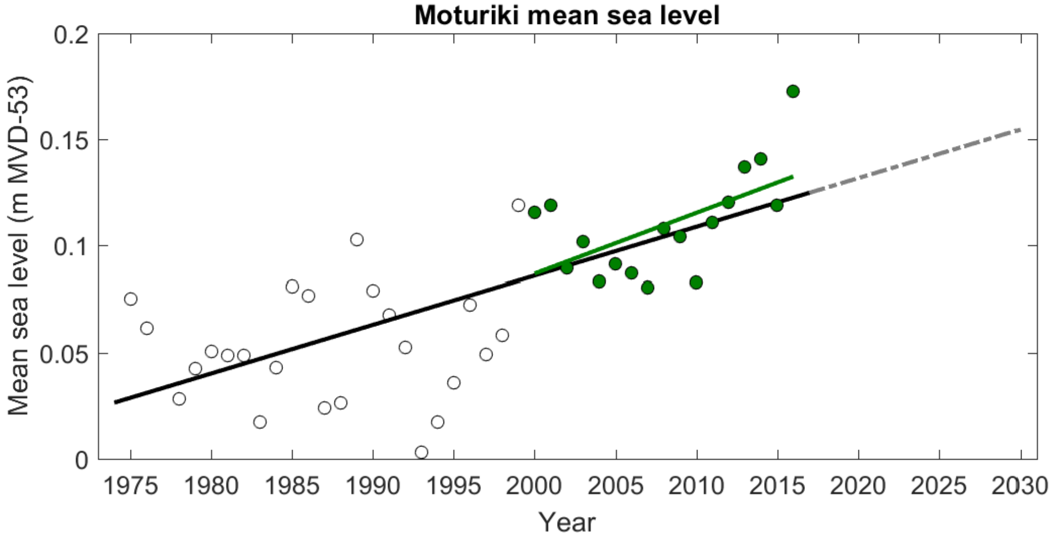

Figure 5-1: Mean sea level at Moturiki. Circles mark annual mean sea level, and lines show fitted linear trends. Filled circles mark annual MSL since 2000. Solid lines mark fitted trends and dashed line shows extrapolation of the historic trend to 2030.

Table 5-1: Mean sea level for different baseline periods at Moturiki. MSL in metres relative to MVD–53. Use Table 4-1 to convert MSL to NZVD2016 datum. 1980–1999 = IPCC AR4 baseline. 1986–2005 = IPCC AR5 baseline. 1999–2008 was used by Hannah and Bell (2012). The 2000–2016 epoch approximately overlaps with the gauges in side Tauranga Harbour.

	1980–1999	1986–2005	1999–2008	2000–2016	Extrapolated to 2020
MSL at Moturiki	0.05	0.07	0.10	0.11	0.13

5.2 Mean sea level in Tauranga Harbour

MSL was calculated from the annual mean of the non-tidal residual. Annual means were only calculated for years where the data record was at least 80% complete. Figure 5-2 plots the annual MSL and linear-trend fits. The Harbour sea-level records are not long enough to calculate reliable long-term sea-level trends, and some of the calculated linear rates of change are beyond what could reasonably be expected due to climate change, indicating that the wharf piles on which the gauges are mounted are probably sinking. Nevertheless, the gauges provide useful estimates of relative MSL.

Table 5-2 presents MSL calculated at each location for several epochs. An average MSL was calculated over the duration of each gauge record. An average MSL over the period 1986–2005, and a projection for 2020 was estimated using a correlation with annual MSL at Moturiki for the overlapping periods. The 1986–2005 average MSL forms the normally used baseline for sea-level rise projections, including scenarios to be used in the forthcoming MfE Coastal Hazards and Climate Change Guidance (MfE under review).[2]

Both the Hairini and Tug Berth gauges measured strong upward trends in MSL, having linear sea-level rise rates of 6.5 and 5.6 mm/year respectively. These rates are much greater than at Moturiki and

[2] Due for release in late 2017.

the NZ average. The high SLR rates are probably influenced be vertical movement in the sea-level gauges, which are probably subsiding because the structure on which the gauges are mounted are sinking into the sediment. Any such subsidence will affect the calculation of MSL. It is also possible that the Tauranga Basin is tilting, and/or vertical land motion is different between gauge sites due to different underlying geology. Continuous GPS monitoring is required to solve this problem in future. I adjusted for assumed gauge subsidence by removing the observed linear rate of sea-level rise of 6.5 and 5.6 mm/year respectively, and adding the long-term linear rate of sea-level rise of 2.1 mm/year, as measured at Moturiki. In making this adjustment I assumed that the sea-level gauges were surveyed to MVD–53 on installation, so the linear correction is applied relative to the first year of record (and relative to 1962 for the Tug Berth gauge). The corrected data are potted in green in Figure 5-2, and used to calculate MSL presented in Table 5-2.

Table 5-2 shows that (Tug Berth aside) MSL is 3–5 cm higher inside Tauranga Harbour than on the open coast at Moturiki. This is to be expected because of the mean tide level (MTL) being slightly set up within an estuary due to friction (the tide not completely draining before the next incoming tide). It is not clear why the Tug Berth gauge at Mount Maunganui has a lower MSL than the other gauges, both before and after correcting for the high rate of measured sea-level change. The Tug Berth gauge zero should be re-surveyed to the nearby benchmarks (especially the primary one BC 84 (code B309) to check on any subsidence of the gauge facility. Oruamatua experiences considerably more interannual variability, which is affecting the short-term trend downwards relative to other sites. The cause appears related to large fluctuations in the non-tidal residual for several months at a time, which can be seen in the smoothed skew-surge in Figure 5-3. The cause of these fluctuations is unknown, but could be related to the geography of the basin and its interaction with wind patterns, or due to sensor drift. Other possibilities suggested by Willem de Lange (*pers. comm.*) are: (i) an accumulation of freshwater within the basin during heavy rain, or (ii) from water being pumped into the basin on high tide, but unable to return through the narrow basin entrance due to persistent wind patterns.

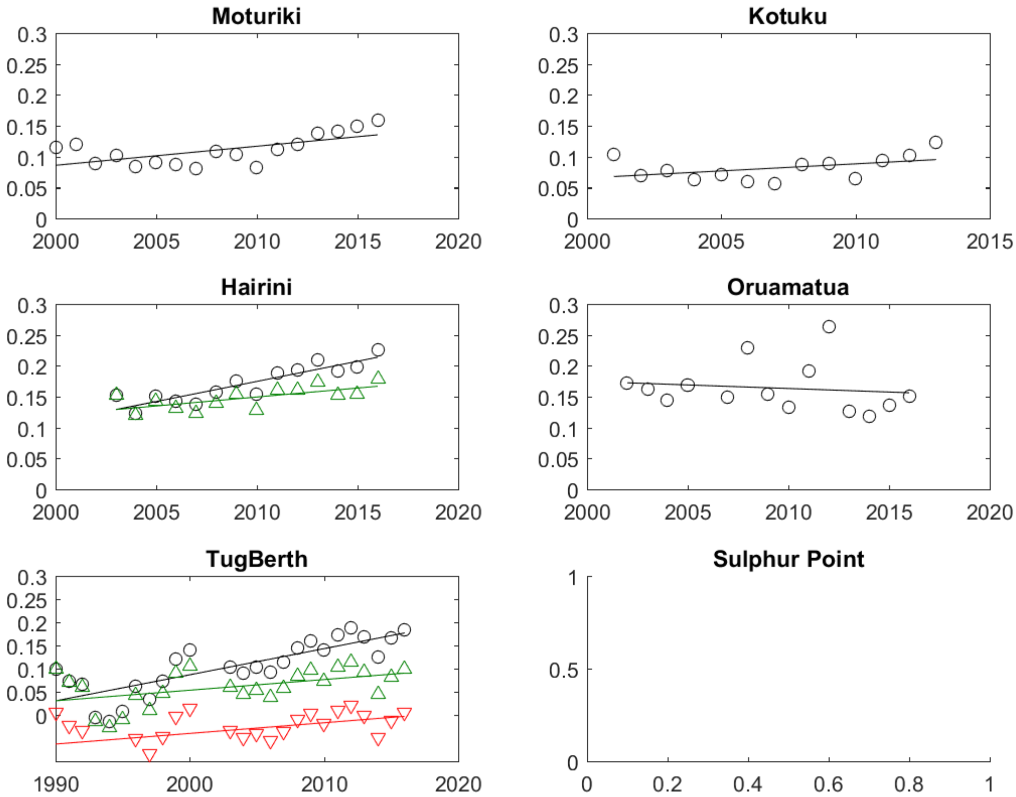

Figure 5-2: Mean sea level trends measured at all sea level gauges. Year is plotted on the *x*-axis and MSL (m MVD–53) is plotted on the *y*-axis. Moturiki is shown only since 2000. At Hairini and Tug Berth, the adjusted MSL and trend are plotted in green, with Tug Berth also adjusted through 1962 origin (red). Insufficient data were available to calculate MSL at Sulphur Point.

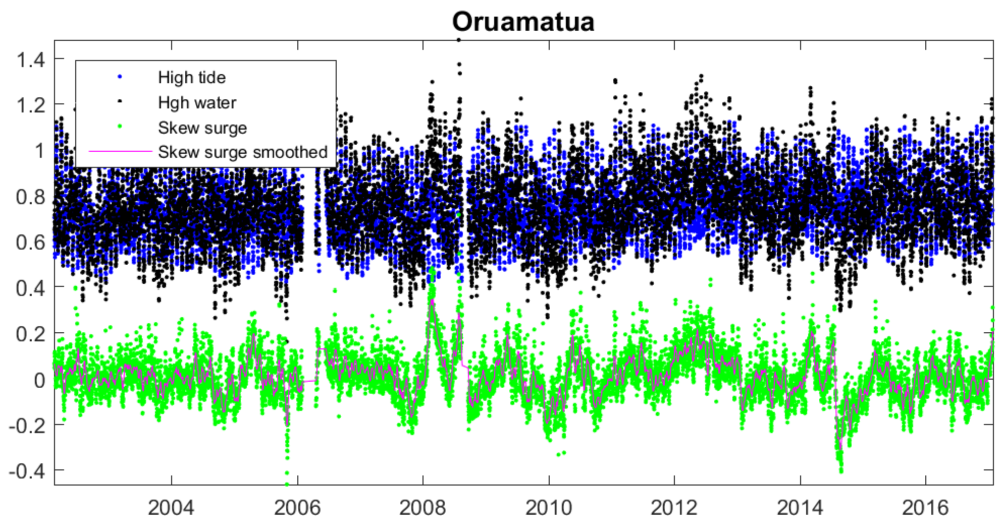

Figure 5-3: High-water and skew surge timeseries at Oruamatua.

Table 5-2: Mean sea level in Tauranga Harbour. MSL in metres relative to MVD–53. Use Table 4-1 to convert MSL to NZVD2016 datum. MSL at Hairini and Tug Berth calculated using data corrected for local gauge subsidence (plotted green in Figure 5-2).

Gauge location	MSL at local gauge for whole record	MSL at Moturiki for overlapping period	MSL offset from Moturiki	Projected MSL by 2020	Estimated local MSL 1986–2005
Kotuku Reserve	0.13	0.10	0.03	0.18	0.09
Hairini Bridge	0.15	0.11	0.04	0.19	0.11
Oruamatua	0.16	0.11	0.05	0.20	0.12
Tug Berth corrected	-0.03	0.09	-0.12	0.01	-0.05 (calculated)
Tug Berth uncorrected	0.10	0.09	0.01	0.16	0.07 (calculated)
Tug Berth corrected through data start	0.06	0.09	-0.03	0.10	0.07 (calculated)
Tug Berth corrected through 1962 origin	-0.03	0.09	-0.12	0.01	-0.05 (calculated)

6 Sea-level rise projections

The New Zealand Coastal Policy Statement requires the identification of areas in the coastal environment that are “potentially affected” by coastal hazards, and assessment of the associated risks over *at least* the next 100 years (Policy 24). This necessitates that some estimate of the rate of SLR be made over at least the next 100 years.

We have selected four SLR scenarios, which are based around three greenhouse gas representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5). Three of the scenarios are derived from the median projections of global SLR for the RCPs presented by IPCC in their Fifth Assessment Report (Church et al. 2013) and extended out to 2130. The fourth higher scenario is at the upper-end of the “likely range” (i.e., 83rd-percentile) of the wide ensemble of SLR projections (from Kopp et al. (2014)) based on emission scenario RCP8.5. We have called this scenario ‘H^+’. This higher H^+ scenario reflects the possibility of future surprises (deep uncertainty) towards the upper range in SLR projections of an RCP8.5 scenario. It is representative of a situation where more rapid rates of SLR could occur early next century from emerging polar ice sheet instabilities or as-yet uncertain understanding of dynamic ice sheet processes. Recent SLR guidance in the USA is using several H^+ scenarios, some considerably larger than that used here (Sweet et al. 2017). A range of SLR trajectories are plotted in Figure 6-1, which also includes the RCP6.0 median scenario for comparison (not selected as it is similar to RCP4.5).

The projected SLR for 2070 and 2130 are shown in Table 6-1, for the wider New Zealand region. The SLR elevations are relative to the MSL over the 1986–2005 baseline period.

To use the projections locally requires that the 1986–2005 mean sea level (MSL) be added, relative to a local vertical datum. MSL at the Moturiki tide gauge was 0.07 m above Moturiki Vertical Datum 1953 (MVD–53) for the 1986–2005 baseline period. The projected SLR relative to MVD–53 are shown in Table 6-2.

There are local differences in MSL (of a few centimetres) throughout the Bay of Plenty region including estuaries, relative to the Moturiki tide gauge (Table 5-1, Table 5-2), some of which may be due to datum or gauge issues.

From the perspective of a specific location on land, such as a human dwelling, intertidal habitat, or water level (tide) gauge, vertical land motion (VLM) also contributes to changes in sea level, and it is this relative sea level rise (RSLR) that is of interest to coastal infrastructure and its inhabitants (Sweet & Park 2014). The rate of VLM in the Pāpāmoa hills was +0.5 mm/yr, measured over approximately 9 years (Beavan & Litchfield 2012; Houlie & Stern 2017). Thus, the land around Tauranga can be considered relatively stable or slightly rising, although rates of VLM can change significantly over 10’s of kilometres, so these may not be accurate when extrapolated to the sedimentary features at the coast. Given the relatively low VLM rates, the distance of the measurement location from the coast, and the relatively short VLM record, we recommend that the SLR values in Table 6-2 be used for the Tauranga coastline, with no additional allowance for VLM. Measurements of VLM are proposed to be collected at the Moturiki sea-level gauge location in the future.

The SLR projections in Table 6-2 apply to the Tauranga region and surrounds, but could differ over the wider Bay of Plenty region due to regional differences in MSL and VLM.

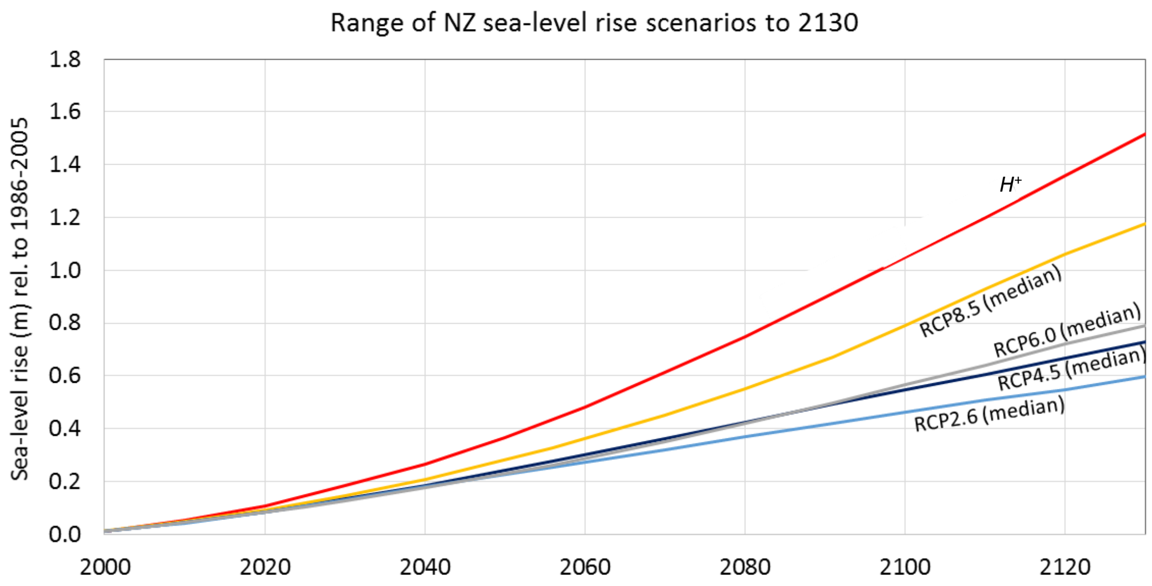

Figure 6-1: Range of sea-level rise scenarios to year 2130. Global average projections have been adjusted for New Zealand by adding up to 0.05 m to cover the slightly-higher expected SLR in the SW Pacific centred in NZ (Ackerley et al. 2013).

Table 6-1: SLR projections (metres above 1986–2005 baseline MSL) in 2070 and 2130 for the wider New Zealand region.

Year	NZ RCP2.6 *M* (median)	NZ RCP4.5 *M* (median)	NZ RCP8.5 *M* (median)	NZ H^+
1986–2005	0	0	0	0
2070	0.32	0.36	0.45	0.61
2130	0.60	0.74	1.18	1.52

Table 6-2: SLR projections (metres above MVD–53) in 2070 and 2130 for the Bay of Plenty region.

Year	NZ RCP2.6 *M* (median)	NZ RCP4.5 *M* (median)	NZ RCP8.5 *M* (median)	NZ H^+
1986–2005	0.07	0.07	0.07	0.07
2070	0.39	0.43	0.52	0.68
2130	0.67	0.81	1.25	1.59

7 High-tide elevations

Tidal elevations were predicted using tidal harmonic analysis, which was applied to each sea-level record.

Tidal harmonic analysis was undertaken using Versatile Harmonic Tidal Analysis (Foreman et al. 2009), applying a signal-to-noise ratio (the ratio of the tidal variance to the non-tidal variance) of 10.

The tide was predicted relative to a MSL of zero, with zero mean and no long-term trend. The solar annual (S_a) and semi-annual (S_{sa}) tides were omitted from the tidal harmonic predictions because harmonic analyses don't always represent the seasonal sea-level cycle well, and most of the seasonal signal is actually driven by non-tidal effects (Boon 2013).

Timeseries of tidal predictions were created by fitting the tidal harmonics and predicting the tides on an annual basis. The tidal predictions are more accurate when resolved on an annual basis, since the tidal harmonic constituents change subtly from year to year. Long-term average tidal harmonic constituents (e.g., M_2, N_2 and S_2 in Table 7-1) were calculated by applying the harmonic analysis to the whole record (epoch-averaged constituents).

The annual tidal timeseries were subtracted from the raw sea-level record to obtain a non-tidal residual sea level. The parameter skew surge, described in Section 2, was calculated as the absolute difference between the maximum recorded sea-level during a tidal cycle and the predicted maximum astronomical tidal level for that cycle, irrespective of differences in timing between these (Batstone et al. 2013).

Table 7-1 gives tidal constituents and mean high-water springs elevations at each of the sea-level gauge locations. MHWS7 is the elevation exceeded only by the highest 7% of all high tides. MHWSn is the nautical definition of mean high-water springs, which is the sum of the M_2 and S_2 tidal constituents. MHWPS is the mean high-water perigean springs elevation, which is the sum of the M_2, N_2 and S_2 tidal constituents. MHW is the mean high water calculated as the average of all high tides. Since MHWS7 is calculated from tidal predictions made on an annual basis, it has more inter-site variability than the MHWSn or MHWPS, which are calculated using epoch-averaged constituents.

Table 7-1: Tidal constituents and mean high-water springs elevations at sea-level gauge locations.

Site	M2	N2	S2	MHWS7	MHWSn	MHWPS	MHW
Moturiki	0.73	0.16	0.10	0.96	0.83	0.99	0.75
Tug Berth / Salisbury Wharf	0.70	0.14	0.09	0.90	0.79	0.93	0.70
Hairini Bridge	0.71	0.14	0.08	0.94	0.79	0.93	0.73
Oruamatua	0.73	0.14	0.09	0.96	0.82	0.96	0.75
Kotuku Reserve	0.72	0.14	0.08	0.91	0.80	0.94	0.72
Omokoroa Wharf	0.72	0.15	0.08	0.97	0.80	0.95	0.77
Sulphur Point / Tauranga	0.71	0.13	0.09	0.88	0.80	0.93	0.70

8 Extreme sea level in Tauranga Harbour

8.1 Extreme-value methods

The objective of an extreme-value analysis is to calculate the likelihood that very large (or small) and rare values could occur, usually for values that are larger than any that have been measured in the typically-short records. There are two ways to do this for sea levels:

1. Fit an extreme-value model to the independent maxima within a data record, and use the model to simulate the frequency and magnitude of large and rare sea levels. There are two of these direct maxima methods in common use, the generalised extreme-value model (GEV) fitted to block (usually annual) maxima, and the generalised Pareto distribution (GPD) fitted to data over a specified threshold called peaks-over-threshold (POT) data.

2. Split the sea-level into its tidal and non-tidal components, which enables to model both separately, and to calculate the likelihood of large and rare combinations of both, which might not (yet) have occurred. These methods are known as indirect joint-probability methods.

Once fitted, the extreme-value models can be checked by plotting them against the measured maxima, assuming that the maxima follow a double-exponential (Gumbel) distribution (Gringorten 1963). The maxima should lie within the confidence intervals of the fitted model.

There are two commonly used ways to express the likelihood of occurrence of an extreme sea level:

- Annual exceedance probability (AEP) – The probability of a given (usually high) sea level being equalled or exceeded in elevation, in any calendar year. AEP can be specified as a fraction of 1 (e.g., 0.01) or a percentage (e.g., 1%).

- Average recurrence interval (ARI) – The average time interval (ideally averaged over a long time period and many "events") that is expected to elapse between recurrences of an infrequent event of a given large magnitude (or larger). A large infrequent event would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years. The term return period is often substituted for ARI.

For this study I used the skew-surge joint-probability model (SSJPM) (Batstone et al. 2013). An advantage of the SSJPM is that it employs skew surge, which allows inclusion of historic skew-surge estimates. The skew-surge distribution obtained from the modern digital measurements was adjusted to account for the historic estimates, and then convolved with the predicted tidal distribution.

Goring et al. (1997) applied the revised joint-probability method (RJPM) to the Moturiki gauge. The RJPM is fundamentally similar to the SSJPM which I have used here, but uses hourly data rather than high-water data. The RJPM is a reliable method for deriving extreme sea levels for high resolution (e.g., hourly) time series of sea-level recordings, but its accuracy is restricted compared to the SSJPM due to the use of the non-tidal residual component to represent the effects of meteorology on sea-levels (i.e., surge). Whilst the non-tidal residual does indeed contain contributions from surge, the values are also determined by tide-surge interaction harmonic prediction errors and gauge timing errors (Batstone et al. 2013). The SSJPM method overcomes, in particular, the tide-surge interaction problem. Goodhue et al. (2015) used the Monte Carlo joint-probability method (MCJP) (Goring et al. 2011) to calculate extreme sea-levels at Moturiki, but this method is not as well suited for use inside the harbour where the different sea-level processes experience non-linear interactions.

Figure 8-1 shows extreme sea levels calculated using the measured sea-level record at Moturiki using four methods (i) GPD fitted to observed maxima, (ii) SSJPM, (iii) an empirical estimate from the CDF of the observed total water levels (TWL) (which is only approximate for small AEP because it doesn't account for serial dependence between high waters), and (iv) the MCJP results from Goodhue et al. (2015). The observed POT maxima are plotted as a check on the fitted models. All methods give approximately the same result, but the width of the confidence intervals is smaller for the joint-probability methods because they use more of the available data than the direct methods. Results for the GPD fit are given in Table 8-1. Note that the results shown in Figure 8-1 and Table 8-1 are statistically valid for the 1974–2017 period of measurement on which they are based, but probably under-predict the true extreme sea-levels because the measurements don't include any very large surges, such as those in 1936, 1954, and 1968. In other words, although the joint-probability methods have tighter confidence intervals than the GPD, the increased confidence is for statistical reasons only. In reality, both methods are likely to be biased low because none of the fits include data from the three large ex-tropical cyclones described in Section 8.2. If more data was available, then the better statistical confidence would confer an advantage.

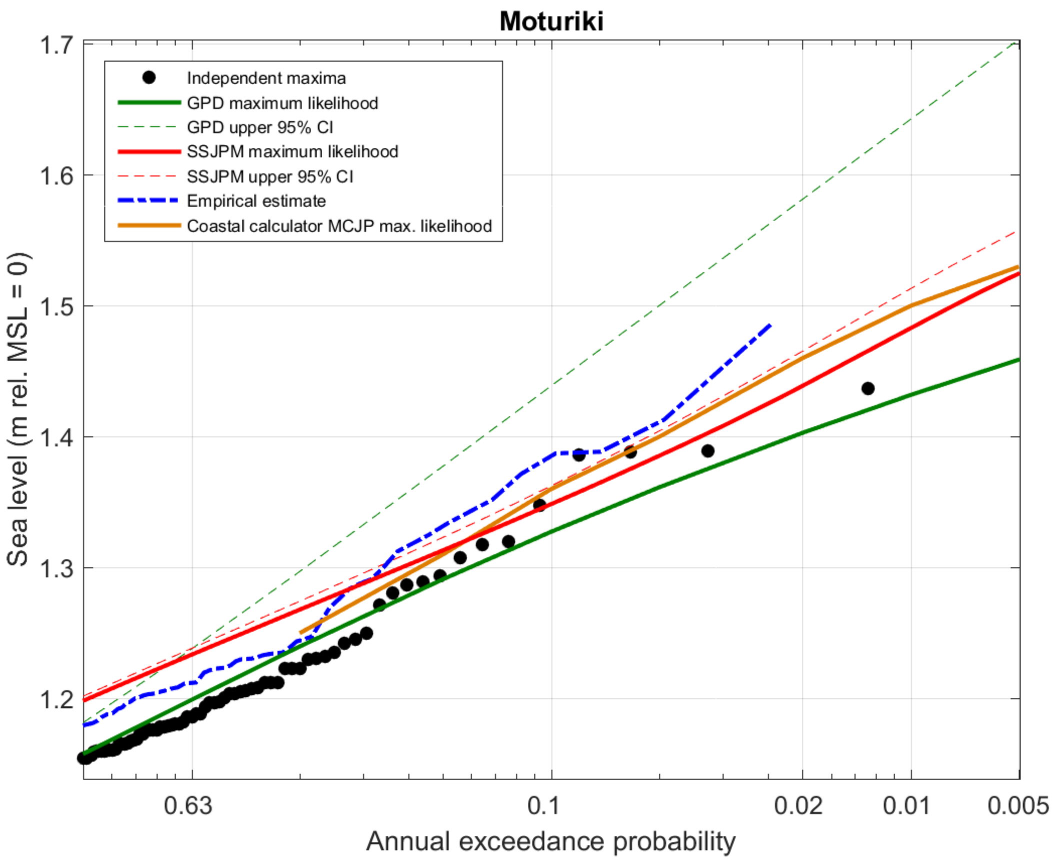

Figure 8-1: Extreme sea level at Moturiki from sea-levels measured since 1974. GPD = generalised Pareto distribution. SSJPM = skew-surge joint-probability method. The plotted storm tide elevations require the addition of a MSL offset to adjust them relative to MVD-53 or NZVD2016. For clarity, only the upper 95% confidence intervals have been plotted, for the GPD and SSJPM methods. This analysis does not consider the three large ex-tropical cyclones discussed in Section 8.2.

Table 8-1: Extreme sea level at Moturiki relative to MVD–53 in year 2020. Includes MSL of 0.13 m MVD–53 extrapolated to 2020 at Moturiki (Table 5-1). This analysis is based on sea-level gauge records from 1974 onward, and does not consider the three large ex-tropical cyclones discussed in Section 8.2.

AEP	ARI	GPD maximum likelihood	GPD lower 95th % confidence interval	GPD upper 95th % confidence interval
0.10	10	1.46	1.38	1.58
0.05	20	1.5	1.4	1.65
0.02	50	1.54	1.42	1.74
0.01	100	1.56	1.43	1.8
0.005	200	1.59	1.44	1.87
0.002	500	1.62	1.45	1.96
0.001	1000	1.64	1.46	2.03

8.2 Historical storm-surges in Tauranga Harbour

Gibb (1997) reports extreme sea levels in Tauranga Harbour sourced from eye-witness accounts of the sea's reach during the major ex-tropical cyclones that caused inundation during 1936, 1954 and 1968. The sea levels were surveyed to MVD–53 datum (Gibb 1997).

The stand-out storm surge events in Tauranga Harbour occurred during ex-tropical cyclones in the so-called "great cyclone" of February 1936, the unnamed ex-tropical cyclone of March 1954 and ex-tropical cyclone *Gisele* in April 1968. Gibb (1997) reports that in the 100 years between 1897 and 1997 there were 87 ex-tropical cyclones that migrated out of the tropics into the New Zealand region. Of these 3 were class 4 events, 27 were class 3 events, and the rest were smaller. Of the 3 class 4 ex-tropical cyclones, two (1936 and 1968) generated significant storm surge in Tauranga Harbour. Of the 27 class 3 ex-tropical cyclones, the unnamed 1954 ex-tropical cyclone produced surges similar to the great 1936 ex-tropical cyclone. The reason the 1954 ex-tropical cyclone was exceptional was that it happened to run into a large blocking high which produced strong winds blowing over a vast fetch to the north-east directly into the Bay of Plenty and Tauranga Harbour (Figure B-1).

These 3 exceptional surge events are clearly much larger than other historical surges, including those measured by sea-level gauges (except for 1968 which was measured at Sulphur Point and Mount Maunganui). The extreme sea-level modelling would under-predict the true inundation hazard if these 3 events were not included in the analysis, i.e., if only the digital sea-level-gauge timeseries only were used (e.g. Figure 8-1).

Table 8-2 reports recorded storm surge elevations for the 3 exceptional events, from Gibb (1997). I have adjusted the storm surges to account for a linear rate of sea-level rise of 2.1 mm/year (Section 5), and commented on notable features.

Table 8-2: Components of historic extreme total water level in Tauranga Harbour (Gibb, 1997). Storm surge elevations were adjusted for sea-level rise.

Location	TWL elevation (m MVD–53)	Predicted high tide height (m)	*storm surge*$_{(Gibb)}$ (m)	Ex-tropical cyclone	MSL (m MVD–53)	MSL-adjusted *storm surge*$_{(Gibb)}$ (m)	Notes
Harbourside restaurant	1.87	0.74	1.13	2 February 1936	-0.06	1.19	Up harbour. Relatively small wave fetch.
Bathing Sheds	2.14	0.74	1.40	2 February 1936	-0.06	1.46	Otumoetai (Kulim Park?)[3]
27 Levers Rd	2.27	0.74	1.53	2 February 1936	-0.06	1.59	Inland - no wave runup?
Omokoroa golf course	2.36	0.74	1.62	2 February 1936	-0.06	1.68	At back of completely-inundated golf course. Little wave runup?
Grace Rd/Harvey St	2.03	0.94	1.09	6 March 1954	-0.02	1.11	Up harbour. Relatively small wave fetch. Inland - no wave runup?
Tilby point	2.44	0.94	1.50	6 March 1954	-0.02	1.52	0.9 m above land surface - true inundation height
Mount Maunganui tide gauge (Salisbury Wharf)	1.4+	0.64	0.76	10 April 1968	0.01	0.75+	Above tide-gauge maximum –true maximum higher
Tauranga tide gauge (Sulphur Point)	1.59	0.71	0.88	10 April 1968	0.01	0.87	
Kulim Park	1.86	0.71	1.15	10 April 1968	0.01	1.14	
77 Beach Road	1.82	0.71	1.11	10 April 1968	0.01	1.10	
27 Levers Rd	1.76	0.71	1.05	10 April 1968	0.01	1.04	Inland - no wave runup?
10 Strange Rd	2.39	0.71	1.68	10 April 1968	0.01	1.67	Higher than others - localised wave runup effects?
Omokoroa golf course	1.91	0.71	1.20	10 April 1968	0.01	1.19	

[3] There was a boat shed on the beach at Otumoetai (Kulim Park?) in 1936, which was used as a bathing shed by Otumoetai School (de Lange *pers. comm.*).

Some of the sea-level observations are located inland of the coast, and could be considered true (widespread) inundation heights above the land surface, as opposed to recording flotsam lines from the localised wave runup maximum along the shoreline edge. These locations occur at 27 Levers Road (1936 and 1968), the back of the Omokoroa golf course (1936), the intersection of Grace Road and Harvey Street (1954), and "0.9 m above the land surface at Tilby Point" (Gibb, 1997), Fergusson Park (1954).

The geography of the harbour influences the size of the surge. Most of these large surges were recorded on the Otumoetai peninsula, which is exposed to relatively large fetches and swell through the Harbour entrance, and would experience increased water levels due to wind and wave setup, and wave runup. On the Otumoetai Peninsula, MSL-adjusted surges of 1.59 m and 1.52 m were recorded in 1968 and 1954. The largest MSL-adjusted surge of 1.68 m was recorded at the back of the Omokoroa golf course; the Omokoroa Peninsula experiences long fetches from the northwest and is prone to wind setup (Willem de Lange, University of Waikato, *pers. comm.*). The historical surges recorded along the waterfront of Tauranga City of 1.19 m at the Harbourside Restaurant (1936) and 1.11 m at Grace Rd/Harvey St (1954), were about 0.40 m lower than those recorded on the Otumoetai Peninsula, probably resulting from lower wind and wave fetch at these more sheltered sites.

On the basis of three class 4 ex-tropical cyclone occurrences and three exceptional storm surge events over the 100-years since 1897, Gibb (1997) suggested a return period of about 1 in 33 years for these large events. It is difficult, however, to accurately define a return period for these exceptional storm-surge events in Tauranga Harbour, given that extreme events can occur in clusters, and from existing records it is unclear whether the last century was typical or abnormal.

Of the 3 exceptional surges in the 120 years since 1897, cyclone *Gisele* in 1968 produced the smallest surges, with the 1936 and 1954 events producing similar-sized surges; the 1936 event being slightly larger than 1954. Notwithstanding that the last 120 years could be atypical, the historic observations suggests approximately three extreme surge events per 120 years. Assuming that these three events will approximately follow a double-exponential (Gumbel) extreme-value distribution, then the expected annual exceedance probabilities for the 3 largest annual-maximum surges would be 0.021, 0.013 and 0.005 (46, 76 and 214-year ARI) for the 1968, 1954 and 1936 surges respectively (using plotting positions based on (Gringorten 1963).

The historical skew surge elevations surveyed by Gibb (1997) were not recorded in the same place as the sea-level gauges, but both types of data are required for extreme sea-level analysis. The sea-level gauge records supply the distribution of tides and the small–medium skew surges, and the historical surges are used to adjust the skew-surge distributions to account for large and rare ex-tropical cyclones. Therefore, I combined the sea-level records (Table 3-1) with the historical surges (Table 8-2), as shown in Table 8-3.

The location of the sea-level gauges, the historical surges used, and the general area of applicability of the extreme sea-level analyses, are shown in Figure 8-2. The output locations for the extreme sea-level analyses are not specifically at the sea-level gauge locations, but are referred to as:

- Hairini Bridge
- Mount Maunganui
- Omokoroa

- Oruamatua
- Otumoetai
- Tauranga.

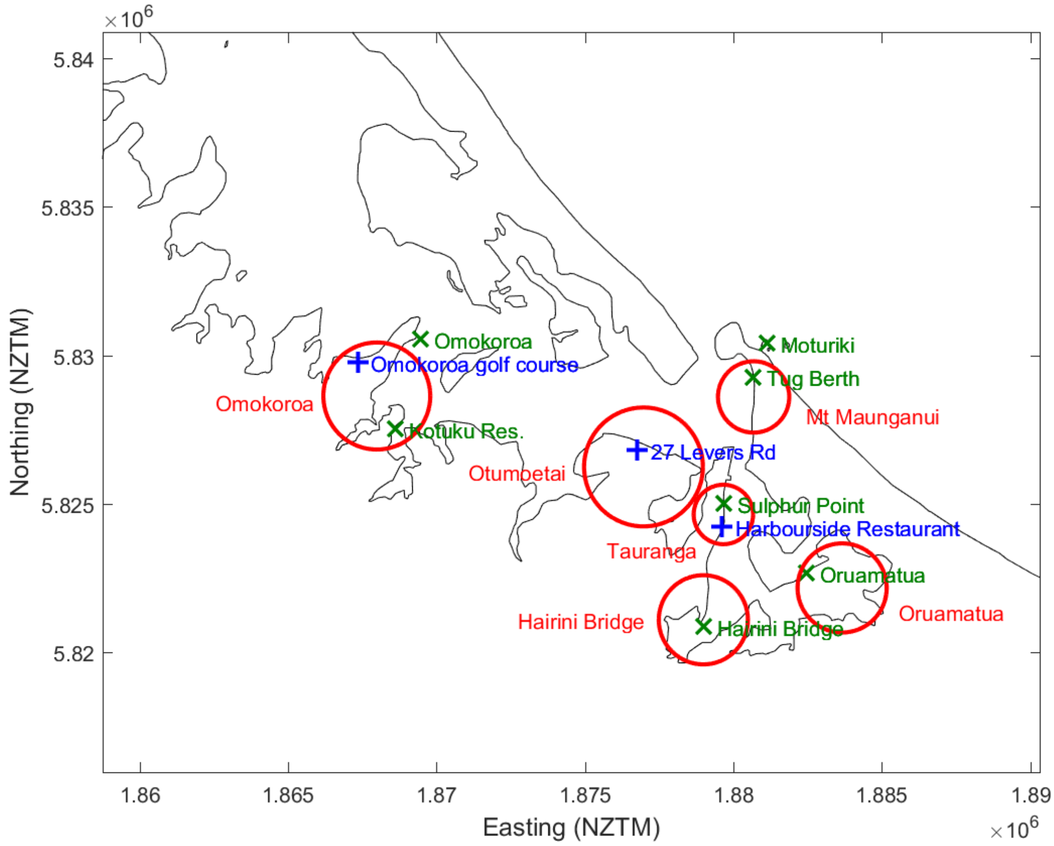

Figure 8-2: Sea level gauge, historical surge survey, and extreme sea-level output locations. The sea-level gauge locations are marked in green. The locations of historical flooding elevations surveyed by Gibb (1997) that were used in the extreme sea-level analyses, are marked in blue. The red circles and labels mark the general area of applicability of the extreme sea-level analysis outputs.

For example, the extreme sea-level analysis for "Otumoetai" uses the Sulphur Point / Tauranga sea-level record and the historic skew surges measured at 27 Levers Road on the Otumoetai Peninsula (Table 8-3). The extreme sea-level analysis for "Omokoroa" uses the Kotuku Reserve sea-level record and the historic skew surges measured on the Omokoroa golf course (Table 8-3).

I used the historical storm surge observations to adjust the extreme skew surge distribution fitted to sea-level gauge records. I identified historical storm surges associated with nearby sea-level gauge sites, and assumed that the largest of these maxima had a return period of 214 years, and that associated with cyclone *Gisele* was the third-ranked maxima and had a return period of 46 years (Table 8-3). Historical observations were available near the sea-level gauge locations at Tug Berth, Tauranga/Sulphur Point, and Kotuku Reserve. For the Hairini and Oruamatua sea-level gauges a scaling factor was derived from the linear correlation with the Tug Berth gauge for the largest 2% of matching surges in the measurement records (Figure 8-3).

Having estimated the height and return period of historical surges at different locations (Table 8-3), I then assumed that the historical maxima could be modelled using a Gumbel extreme-value distribution, which is a relatively simple distribution to fit through two data points. Figure 8-4 shows the extreme storm surge distribution calculated from the measured data at Sulphur Point / Tauranga, and shows a Gumbel extreme-value distribution fitted to the historic maxima at nearby Otumoetai. The historic surges lie outside the 99% confidence intervals obtained from the measured data – indicating that they come from a different population of meteorological events. The confidence intervals of the extreme-value distribution representing the historic events were estimated by assuming 99% confidence intervals of about ±0.25 m about the median at 0.005 AEP. This is a somewhat arbitrary choice, but provides 99% confidence intervals that range from about 60–190 years for a 100-year ARI event, which seems reasonable given the data at hand. The maximum storm surge height is physically limited, but the Gumbel model continues to increase, therefore the maximum surge was limited to 2.0 m during extreme sea-level modelling.

For extreme sea-level modelling, the two extreme surge distributions (Figure 8-4) were merged, with the Gumbel distribution being used at low AEP, wherever it returned higher surge estimates than the GPD distribution. This leads to a slightly disjointed skew-surge distribution, but represents the existence of two separate populations of events.

In recognising that there are two "populations" of events in the data it is worth re-iterating that the populations are different for two reasons: (i) the storms that created them were unique and much larger than normal, and (ii) the data were collected differently – the modern digital sea-level gauge data contains no wave effects whereas the surveys of historic data contain wave effects to an unknown degree.

Table 8-3: Extreme sea-level outputs locations matched to the sea-level gauge and historical skew surge amplitude used for their calculation. Also shown are the estimated return periods for the historic skew surges.

Extreme sea-level analysis output location	Sea-level gauge (Table 3-1)	ARI (years)	Skew surge (m)	Historic skew surge (Table 8-2)
Otumoetai	Sulphur Point / Tauranga	46	1.04	27 Levers Road, cyclone Gisele
		214	1.59	27 Levers Road, 1936 great cyclone
Mount Maunganui	Tug Berth / Salisbury Wharf	46	0.88	Sulphur Point tide gauge, cyclone Gisele
		214	1.19	Harbourside restaurant, 1936 great cyclone
Omokoroa	Kotuku Reserve	46	1.19	Omokoroa golf course, cyclone Gisele
		214	1.68	Omokoroa golf course, 1936 great cyclone
Tauranga	Sulphur Point / Tauranga	46	1.19	Omokoroa golf course, cyclone Gisele
		214	1.68	Omokoroa golf course, 1936 great cyclone
Hairini	Hairini Bridge		0.94 × Lower Harbour	Based correlations of top 2% of skew-surges with Tug Berth gauge
Oruamatua	Oruamatua		1.22 × Lower Harbour	Based on correlations of top 2% of skew-surges with Tug Berth gauge

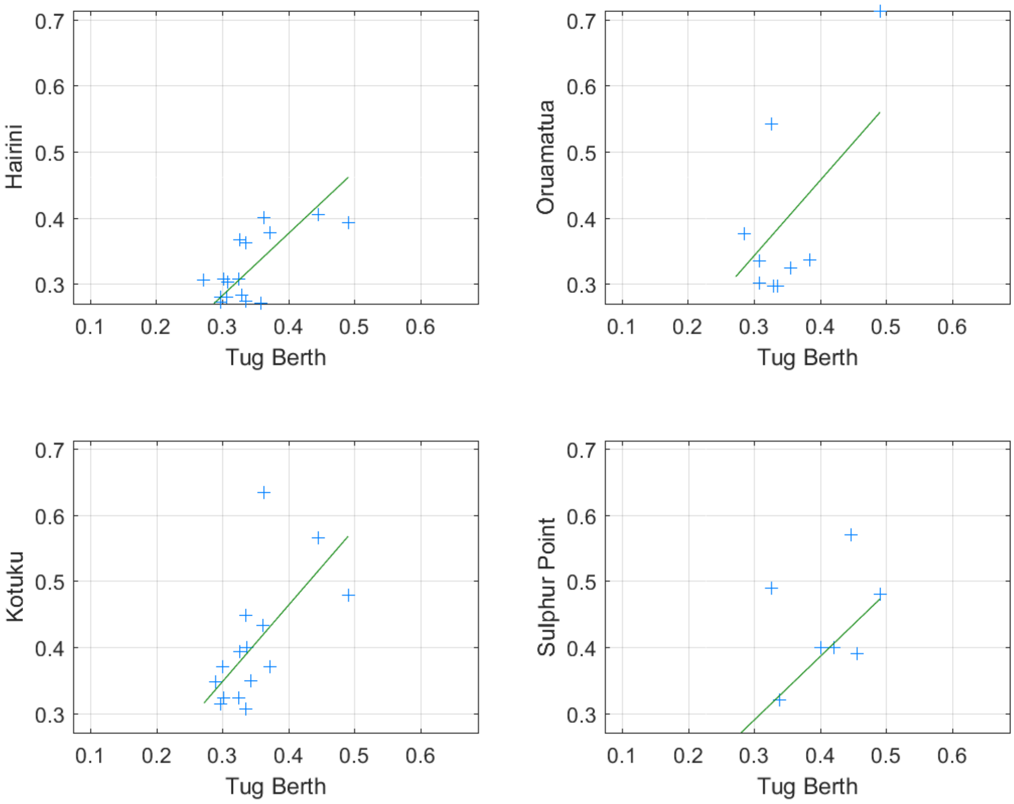

Figure 8-3: Comparison between large skew surges measured at Tug Berth with other gauges. Only surges in the top 3% are compared, except at Sulphur Point where all surges associated with matching annual maxima from Table C-1 are plotted (some outside the axis margins). Linear fits through 0,0 are also plotted.

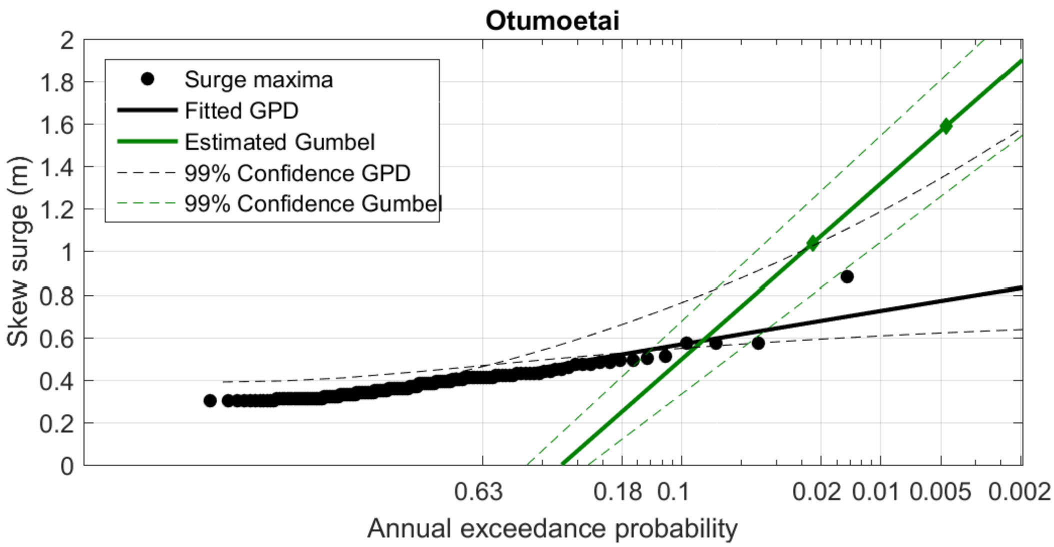

Figure 8-4: Extreme skew surge at Otumoetai from measured levels at Sulphur Point / Tauranga (black dots), plus estimated distribution for the three exceptional events at Otumoetai, fitted through the largest and smallest (green diamonds). GPD = generalised Pareto distribution, fitted to independent surge maxima.

8.3 Extreme sea level in Tauranga Harbour

Extreme sea levels inside the Tauranga Harbour were calculated using the SSJPM method (Section 8.1). Extreme sea levels at the Tauranga Harbour sea-level gauge sites are plotted in Figure 8-5 and presented in Table 8-4 and Table 8-6, the values in Table 8-6 being relative to MVD–53 in the year 2020. For comparison, the maximum potential sea levels are shown in Table 8-5 (calculated using a "building block" technique, which combines maximal values of individual components). At 0.002 AEP (500-year ARI) the maximum potential total water levels, including the large historical storm surges, ranges from -0.05–0.21 m above the upper 95th percent confidence interval of the extreme-value fits.

The more common extreme sea levels, those with AEP ≥ 0.1 (10%), are influenced mostly by high tides combining with relatively small surges. Thus, the difference between sites at AEP ≥ 0.1 is due mainly to the difference in tidal elevations (Figure 8-5). At AEP < 0.1, the inter-site differences in the extreme storm-surge distributions (Table 8-3) becomes influential. The difference in surge distribution is the dominant cause of the difference in predicted extreme sea-level at low AEP. Thus, the predictions of the most extreme sea levels are highly sensitive to the reliability of Gibb's (1997) eye-witness accounts of the 1936, 1954 and 1968 surges. Omokoroa and Otumoetai have the largest extreme sea levels reflecting the exposure to large wind fetches. Oruamatua reflects the surge amplification within the Oruamatua basin relative to Tauranga. Hairini has the lowest predicted extreme sea levels, reflecting the dissipation of both tides and surge into the Hairini basin.

Extreme sea levels inside the Tauranga Harbour were calculated using combinations of sea-level gauge data and historic skew surge measurements (Table 8-3). However, the output locations for the extreme sea-level analyses do not always exactly match the sea-level gauge locations (Figure 8-2). This is a major assumption, because the tide and surge characteristics can change substantially over relatively short distances due to the convoluted shape of the Harbour and its seabed, and changing wind fetch. For example, the extreme sea-level analysis at Omokoroa uses the Kotuku Reserve sea-level record, combined with historical surges measured at Omokoroa on the other side of Omokoroa Peninsula. The Kotuku Reserve gauge was located inside the Te Puna estuary, and tides differ with those measured at Omokoroa Wharf. Furthermore, the wind setup differs considerable on either side of Omokoroa Peninsula (de Lange *pers. comm.*). The mixing of datasets is not ideal, but is unavoidable because the extreme-value analyses must be supported by an underlying full sea-level distribution (from the gauges), but must also include an estimate of the large historic surges, without which the extreme sea levels would be badly under-predicted.

Fortunately, because the large low-frequency events are dominated by the large historic surges (and their associated uncertainties), the use of a nearby sea-level gauge record becomes of secondary importance to the accuracy of the extreme sea-level analysis.

The mixing of gauge and historic observations from different locations leads to additional uncertainty in the extreme sea-level estimates. Numerical hydrodynamic models offer a potential solution, enabling the tidal distributions from the gauged sites to be related to sites at which the historical surge estimates were collected. Numerical models could also be used for testing wind-surge generation inside the harbour.

A further source of uncertainty are the bathymetric changes that have occurred since the 1980s, due to dredging and reclamation within the harbour. The large historic skew surges and some of the sea-level data at Sulphur Point / Tauranga, pre-dates the bathymetric changes. The extent to which these changes will affect the extreme sea-level analyses is unclear. I think they will have minor affect for most of the harbour, but could be locally important, such as at Sulphur Point where there have been pronounced changes. Again, numerical models offer a solution, once calibrated, and can represent the modern harbour and its response to extreme sea-level events.

The extreme sea-level analyses can guide future numerical modelling inside the harbour. The analyses estimate the likely frequency of occurrence of extreme sea-levels, so will be useful when designing modelling scenarios. A useful approach would be to use the hydrodynamic model to run sensitivity tests, to examine the response of the total water level in the harbour to various tide, wind and wave scenarios. These will show up spatial differences in the Harbour, which can be put in context with the extreme sea-level analyses, and used to infer how the extreme sea-level analyses might be applied or adjusted within the harbour.

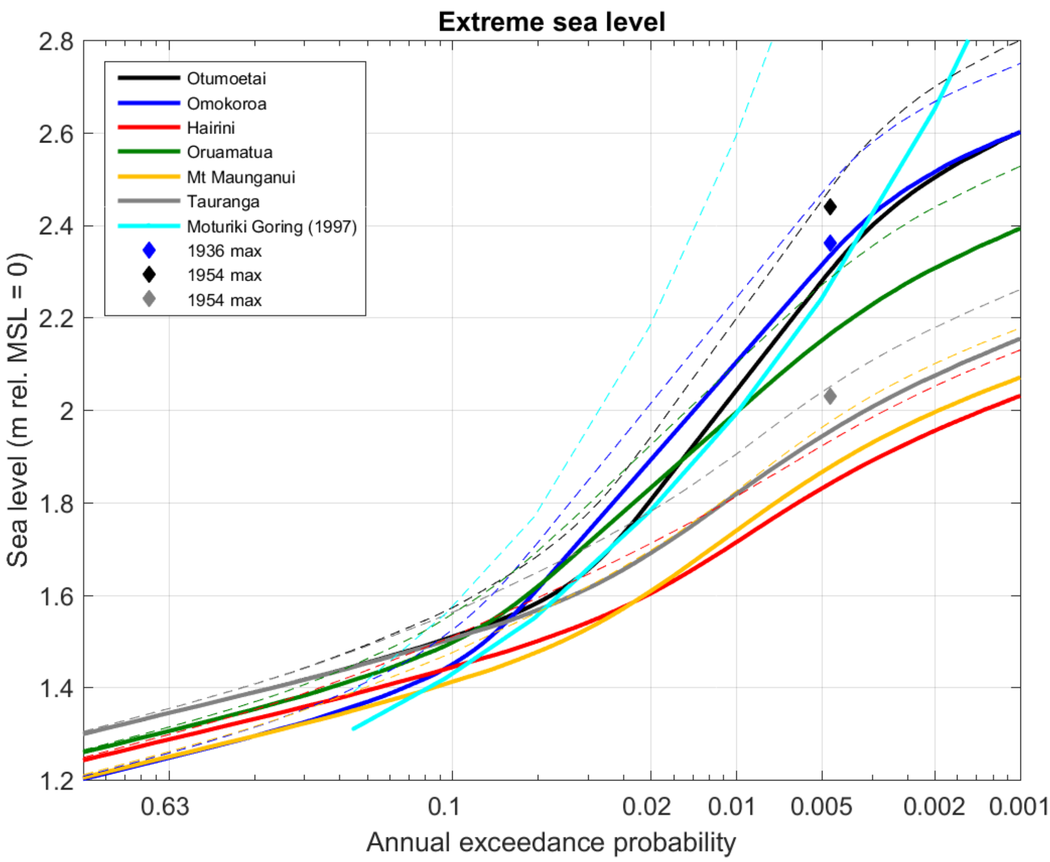

Figure 8-5: Extreme sea levels in Tauranga Harbour. Sea levels require the addition of MSL to make them relative to MVD–53. Dashed lines represent upper 95% confidence intervals. Extreme sea levels were calculated using the SSJPM method, except at Moturiki where the Goring et al. (1997) RJPM results are used. Historic maxima are plotted using Gringorten (1963) plotting position for the annual maximum in a 120-year sequence.

Table 8-4: Extreme sea levels in Tauranga Harbour. Levels are in metres above MSL=0. Levels require the addition of a MSL offset to make them relative to MVD–53.

	AEP	0.1	0.02	0.01	0.005	0.002
	ARI	10	50	100	200	500
Mount Maunganui	Lower	1.38	1.54	1.66	1.77	1.89
	Median	**1.41**	**1.61**	**1.74**	**1.87**	**1.99**
	Upper	1.48	1.70	1.82	1.96	2.10
Tauranga	Lower	1.48	1.62	1.74	1.85	1.97
	Median	**1.51**	**1.69**	**1.82**	**1.94**	**2.07**
	Upper	1.56	1.78	1.90	2.04	2.18
Otumoetai	Lower	1.48	1.68	1.90	2.11	2.32
	Median	**1.51**	**1.80**	**2.04**	**2.28**	**2.50**
	Upper	1.57	1.94	2.20	2.45	2.70
Omokoroa	Lower	1.41	1.78	1.97	2.17	2.35
	Median	**1.45**	**1.89**	**2.10**	**2.31**	**2.51**
	Upper	1.52	2.01	2.24	2.47	2.67
Oruamatua	Lower	1.46	1.74	1.90	2.04	2.19
	Median	**1.50**	**1.83**	**1.99**	**2.15**	**2.31**
	Upper	1.56	1.92	2.10	2.27	2.44
Hairini	Lower	1.42	1.54	1.64	1.75	1.86
	Median	**1.44**	**1.60**	**1.71**	**1.83**	**1.95**
	Upper	1.51	1.71	1.81	1.92	2.05

Table 8-5: Maximum potential sea levels in Tauranga Harbour using a "building block" approach for maximal values of the components. Sea levels require the further addition of MSL to make them relative to MVD–53. Only measured maxima are included – the potential for larger surges is not considered.

Site	MSLA	Tide	Measured surge	Maximum (measured) potential TWL	Historical surge	Maximum (historical) potential TWL
Mount Maunganui	0.17	1.07	0.88	2.12	0.88	2.12
Tauranga	0.17	1.21	0.75	2.13	0.75	2.13
Omokoroa	0.14	1.06	0.55	1.75	1.68	2.88
Oruamatua	0.40	1.12	0.51	2.03	1.07	2.59
Hairini	0.24	1.12	0.38	1.74	0.83	2.19
Moturiki	0.15	1.14	0.53	1.82		

Table 8-6: Extreme sea levels in Tauranga Harbour relative to MVD–53, including 2020 MSL (projected). Projected MSL for 2020 are given in Table 5-2.

	AEP	0.1	0.02	0.01	0.005	0.002
	ARI	**10**	**50**	**100**	**200**	**500**
Mount Maunganui	Lower	1.51	1.67	1.79	1.90	2.02
	Median	**1.54**	**1.74**	**1.87**	**2.00**	**2.12**
	Upper	1.61	1.83	1.95	2.09	2.23
Tauranga	Lower	1.58	1.72	1.84	1.95	2.07
	Median	**1.61**	**1.79**	**1.92**	**2.04**	**2.17**
	Upper	1.66	1.88	2.00	2.14	2.28
Otumoetai	Lower	1.58	1.78	2.00	2.21	2.42
	Median	**1.61**	**1.90**	**2.14**	**2.38**	**2.60**
	Upper	1.67	2.04	2.30	2.55	2.80
Omokoroa	Lower	1.57	1.94	2.13	2.33	2.51
	Median	**1.61**	**2.05**	**2.26**	**2.47**	**2.67**
	Upper	1.68	2.17	2.40	2.63	2.83
Oruamatua	Lower	1.64	1.92	2.08	2.22	2.37
	Median	**1.68**	**2.01**	**2.17**	**2.33**	**2.49**
	Upper	1.74	2.10	2.28	2.45	2.62
Hairini	Lower	1.59	1.71	1.81	1.92	2.03
	Median	**1.61**	**1.77**	**1.88**	**2.00**	**2.12**
	Upper	1.68	1.88	1.98	2.09	2.22

8.4 Comparison with previous studies

Blackwood (1999), on behalf of T&T (1999), calculated the frequency and magnitude of extreme sea levels using the Tug Berth gauge data, and also using Moturiki gauge data for comparison with joint-probability results by NIWA (Goring et al. 1997). Blackwood (1999) used direct methods, fitting extreme sea-level distributions to observed maxima (reproduced in Table C-1). Since the Tug Berth gauge jammed during cyclone *Gisele*, the 1.59 m MVD–53 elevation measured at Sulphur Point was substituted. Blackwood used sound methods and applied good judgement in his analysis. However, we now know that the two outlying annual maxima at Moturiki in 1977 and 1980 were false readings. This leads to a different conclusion to Blackwood, who found that extreme sea levels don't necessarily correlate inside and outside Tauranga Harbour, and can be much larger at Mount Maunganui; Figure 8-6 of this report suggests that they are correlated. Blackwood (1999) provides lower extreme sea levels for Mount Manganui (Tug Berth gauge) than the results presented here (Table 8-6), because the direct maxima methods used can't account for combinations of tide and surge values more extreme than have occurred in the measured record, and the measured record did not include the two largest historical storm tides in 1936 and 1954. T&T (2008) used similar methods to the 1999 study and achieved similar results. Blackwood's conclusions were reasonable given the available data and methods at that time, but the use of joint-probability methods and more comprehensive data availability leads to different conclusions here.

Goring et al. (1997) applied the revised joint-probability method (RJPM) to the Moturiki gauge. The RJPM is fundamentally similar to the SSJPM used here, but uses hourly data rather than high-water data. The RJPM is a reliable method for deriving extreme sea levels for high resolution (e.g., hourly) time series of sea-level recordings, but its accuracy is restricted compared to the SSJPM due to the use of the non-tidal residual component to represent the effects of meteorology on sea-levels (i.e., surge). Whilst the non-tidal residual does indeed contain contributions from surge, the values are also determined by tide-surge interaction harmonic prediction errors and gauge timing errors (Batstone et al. 2013). The SSJPM method overcomes, in particular, the tide-surge interaction problem, and intertidal variations in surge and wave exposure. However, on the open coast at Moturiki, tide-surge interaction should be small, so we would expect similar results from the RJPM and SSJPM methods. Goring et al. (1997)'s RJPM methods results are plotted alongside my results in Figure 8-5. They agree closely to my results for Otumoetai and Omokoroa. In both the RJPM and SSJPM an extreme value distribution is fitted to the upper tail of the non-tidal residual (surge) distribution in order to model the probabilities of values higher than the highest in the observation record. Goring et al. (1997) do not explain how this was achieved, and Derek himself cannot recall what was done (Derek Goring *pers. comm.*), but the match to my results shows that they also enhanced the tail of the extreme storm surge distribution in some way. When Goring et al. (2011) applied a (different) joint-probability method[4] to the Moturiki data, using only the modern hourly measured data (including only relatively small surges) the extreme sea-level heights were similar to those obtained from direct maxima methods, but were much smaller than the values predicted here (Table 8-6) and plotted in Figure 8-5.

[4] An alternative joint-probability method, but the assumption of independence between tide, MSLA, surge and makes it less-well suited for application inside harbours.

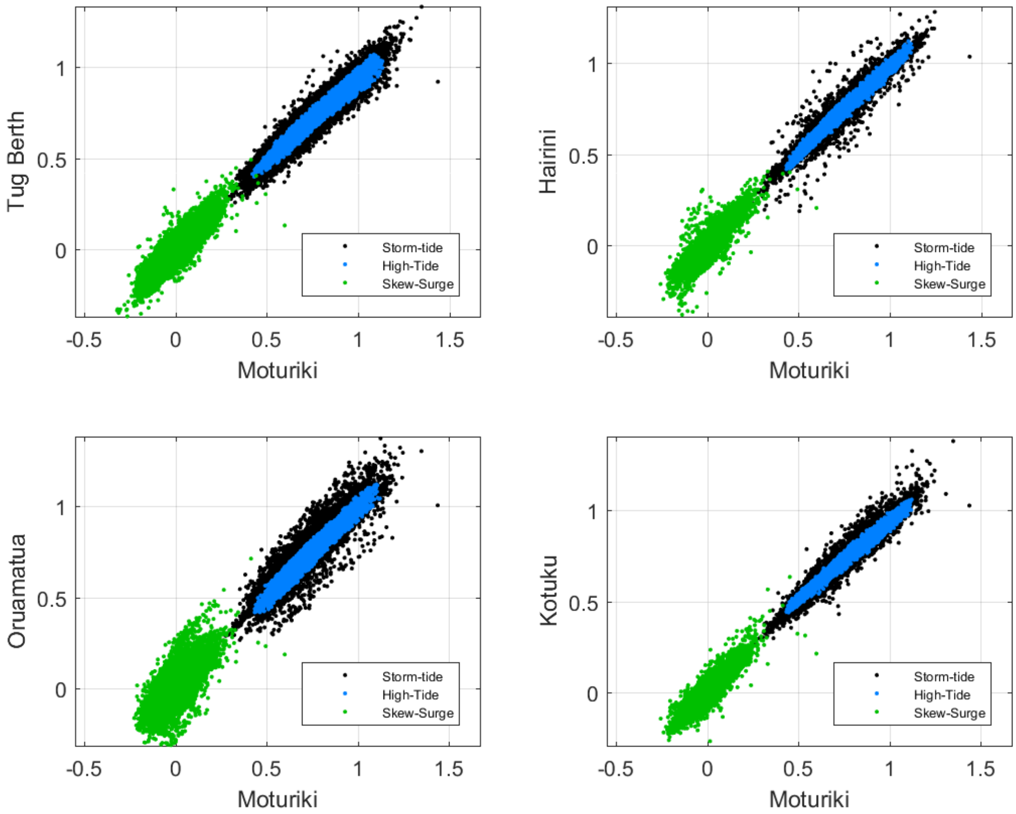

Figure 8-6: Correlation between Tauranga Harbour sea levels and those on the open coast at Moturiki. The relationship between tide, skew surge, and total water level is linear, albeit with increased scatter amongst the largest surges. Values are specified in are metres relative to MSL = 0.

9 Acknowledgements

Thanks to Dr Willem de Lange of the University of Waikato who supplied high-water data from Sulphur Point from 1960–1998, and advised on the location of tide gauges. A review by Dr de Lange improved aspects of this report, and some of his comments were included. Thanks to Mike Tyler for sourcing Tug Berth data from the Port of Tauranga. Thanks to the Port of Tauranga for the supply of sea-level data during this and previous studies.

The work of Gibb (1997) provides a record of historical high sea-level events in Tauranga Harbour, which has added great value to the present study and other preceding hazard studies. Benjamin Robinson processed and quality analysed the hourly sea-level data. The sea-level rise projections are based on Dr Rob Bell's contribution to the MfE (2017) guidance.

NIWA's Rotorua office maintains and runs the Moturiki sea-level gauge which is an invaluable resource for regional coastal hazards and national and international climate-change studies.

10 Glossary of abbreviations and terms

Annual exceedance probability (AEP)	The probability of a given (usually high) sea level being equalled or exceeded in elevation, in any calendar year. AEP can be specified as a fraction of 1 (e.g., 0.01) or a percentage (e.g., 1%).
Average recurrence interval (ARI)	The average time interval (averaged over a long time period and many "events") that is expected to elapse between recurrences of an infrequent event of a given large magnitude (or larger). A large infrequent event would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years.
Epoch	A particular period of history that is arbitrarily selected as a point of reference – used in connection with developing a baseline sea level.
Joint-probability	The probability of two separate processes occurring together (e.g., high tides and high storm-surge).
MVD-53	Moturiki Vertical Datum-1953 is the local vertical datum used in the Bay of Plenty region.
MHWS	Mean high water springs – The high tide height associated with higher than normal high tides that result from the beat of various tidal harmonic constituents. Mean high water springs occur every 2 weeks approximately. MHWS can be defined in various ways, and the MHWS elevation varies according to definition. This has led to subjectivity when defining the CMA for RMA purposes but this report provides a pragmatic solution that builds in variability in tide range and the effect of wave setup on open coasts.
MSL	Mean sea level – the mean level of the sea relative to a vertical datum over a defined epoch, usually of several years.
MSLA	Mean sea-level anomaly – the variation of the non-tidal sea level about the longer term MSL on time scales ranging from a monthly basis to decades, due to climate variability. This includes ENSO and IPO patterns on sea level, winds and sea temperatures, and seasonal effects.
SLR	Sea-level rise.
Storm-surge	The temporary rise in sea level due to storm meteorological effects. Low-atmospheric pressure causes the sea-level to rise, and wind stress on the ocean surface pushes water down-wind and to the left up against any adjacent coast.
Storm-tide	Storm-tide is defined as the sea-level peak during a storm event, resulting from a combination of MSL + SLA + tide + storm-surge. In New Zealand this is generally reached around high tide.

Wave overtopping	Wave overtopping occurs when the wave runup exceeds the crest elevation of the beach. Overtopping by wave runup involves “wave splash”, “wind spray” and sporadic shallow overwash of “green water” over the beach crest and onto the backshore. Wave overtopping is measured in litres per second per metre length of crest. Wave overtopping may not necessarily cause substantial flooding depending on the back-shore drainage capacity.
Wave runup	The maximum vertical extent of sporadic wave “up-rush” or flowing water (“green water”) on a beach or structure above the still water or storm-tide level, and thus constitutes only a short-term upper-bound fluctuation in water level compared to wave setup.
Wave setup	The increase in mean still-water sea level at the coast, resulting from the release of wave energy in the surf zone as waves break.

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Appendix A Quality analysis of sea-level data

The procedure for quality assurance of the sea-level data was undertaken as follows:

1. Copy the original file and save it with a new name ready for quality analysis (QA). Original file versions must be preserved.

2. Divide timeseries into timestep-sections having equal (or approximately equal) timestep. Some sea-level timeseries will have a consistent timestep all the way through. Other files may have a change in sampling frequency due to gauge upgrades/maintenance. A change in timestep can cause problems for harmonic prediction, smoothing and decimation.

3. Predict tides using Unitide software (Foreman et al. 2009).

4. Calculate non-tidal residual (NTR). The basis of quality control is the inspection of residuals, defined as observed data minus predicted tides:

    i. Work with each timestep-section separately.

    ii. Trim missing data from ends of timeseries.

    iii. Forecast tide using local CNS, then interpolate tide to the time of measured timeseries. This can be an approximate tidal prediction based on a CNS file. More detailed tidal prediction comes later.

    iv. Subtract predicted tide to obtain NTR.

5. De-spiking. A data spike is an obviously wrong data point. A glitch is one or more, but less than or equal to 24 hours of consecutive obviously wrong data points. These features are easily identified on plots of residuals. Fluctuations in the residuals are considered significant if they are greater than 0.25 m. However, each case is subjectively analysed to determine if the fluctuation is a natural event, an indication of mechanical problems with the gauge or instrument setting, or a result of unreliable predicted tides. For high-frequency data (e.g., sampled at 1- or 5-min intervals), spikes can affect subsequent averaging and decimation to 1-hour intervals, and so should be removed first. Large waves can cause bubbler gauges without bell-housings to underestimate the sea level, and can be seen as large negative spikes. Having identified large spikes, these are either deleted, or interpolated over, and the changes documented in the log file. Linear interpolation is preferable for high frequency datasets (e.g., 1 to 5 minutes), deletion for hourly data. The best procedure for filling gaps is to replace the missing data flags with quality controlled data from an auxiliary sea level gauge that is linked to the same datum. This is probably best done with hourly data. If a redundant sensor in not available, then another good method is linear interpolation via the predicted-tide method. The predicted-tide method for filling gaps requires yearly files of observed and corresponding predicted data. To do this requires a high-quality annualised tidal-harmonic prediction. The predicted tides are shifted in time to match the timing characteristics of the observed series. The residuals between the predicted tides and the observed data are calculated. Then, a linear interpolation between the end points of the gap in the residual series is performed and each interpolation constant is added to the shifted predicted tides over the span of the gap. The UHSLC recommends using this procedure only for gaps less than or equal to 24 hours. This is essential for the integrity of the daily data which can be calculated from the hourly data. All spike removal and interpolation is logged.

6. Look for timing errors. Timing errors are introduced into the data due to mistakes during data processing, to incorrect setting of the timer on the tide gauge, or to inaccuracies in the gauge time clock. The errors are evident in the plot of residuals as periodic fluctuations. Residual plots can reflect inaccuracies in either the observed data or the tide predictions. The ability for the tidal analysis to fully model the tidal species depends greatly on the location. For gauges in ports adjacent to deep waters, the analysis is usually very good. For gauges in regions with influence of rivers, shallow coastal shelves, narrow basins, or complex basin bathymetry, the analysis is of low to moderate quality. In this case, assuming the observed data are good, the residuals with show periodic fluctuations for tidal species that were not resolved by the tidal analysis. Most timing errors are exactly one hour. These often occur during the change over from New Zealand standard time (NZST) and New Zealand daylight-savings time (NZDT). In some older hourly sea-level records (e.g., Dunedin), there are timing drifts that appear to incrementally increase with time, before being reset. Presumably these arose from drifts in the timing clock of the sea-level recorder. In this case a time-lagged timing correction should be applied.

7. Delete erroneous data. Sometimes the gauge will be faulty but will still record sea level values. This often occurs when damage such as storm damage to the gauge has occurred. The non-tidal residual is used to find these errors, which manifest as nonsensical readings, as in Green Island below. Such errors continue over a period of a few hours, to a few days or longer. The only course of action in these cases is to delete the erroneous section from the record and replace with missing data flags.

8. Decimation and merging of datasets. If using high-frequency data, then decimation to hourly data is often useful. Hourly data is sufficient for most purposes, such as resolving tides, storm surge, mean-sea-level anomaly and mean sea level. Hourly data is easier to work with (less of it) than high-frequency data. High-frequency data should be retained for analysis of tsunami, meteorological tsunami and seiche. Before decimation, it may be advantageous to first correct any timing errors (see 6) and reference level shifts (see 7), since either of these could potentially fall between decimation points. Conversely, it is easier to work with and correct these errors using hourly data, at trade-off of possible (small) loss in accuracy.

9. Look for reference level shifts. Improper sea-level gauge calibration leads to reference level shifts. This could be from resetting of the gauge zero by a technician, a malfunction of the gauge (e.g., the slippage of the gauge cable [sudden shift] or biofouling such as growth over the bubbler orifice [gradual drift] such as occurred at Sumner head 2004–2006), or the vertical displacement of the tide staff. Most shifts are readily identifiable in hourly residual plots. They can also be seen in plots of the daily and monthly data and in plots of differences of daily or monthly values with nearby tide stations or with redundant sensors at the site in question. If a shift is identified, the proper means of correction is through analysis of the tide staff readings or nearby gauge record, and corresponding tide gauge values. In some New Zealand examples neither staff gauge or nearby sea-level gauge records are available, in which there is little to guide the process other than by eyeballing the plots and expert judgement. Daily, monthly and annual means can be calculated and compared with a nearby sea-level gauge. Any required reference level shifts are logged.

10. Final revision. Having undertaken full QA the final step is to review the QA'd timeseries. Steps to follow are:

i. Re-forecast the tides on an annualised basis, using the QA'd timeseries, and calculate NTR.

ii. Re-examine the residuals – is there remaining evidence of erroneous data? A useful technique for finding remaining errors is to decompose the sea-level into various components using filters, and to plot the various components. Timing errors and spikes are often particularly visible in the high-frequency component, while reference level shifts can stand out in the low-frequency component.

Appendix B Weather map 18:00 UTC 6 March 1954

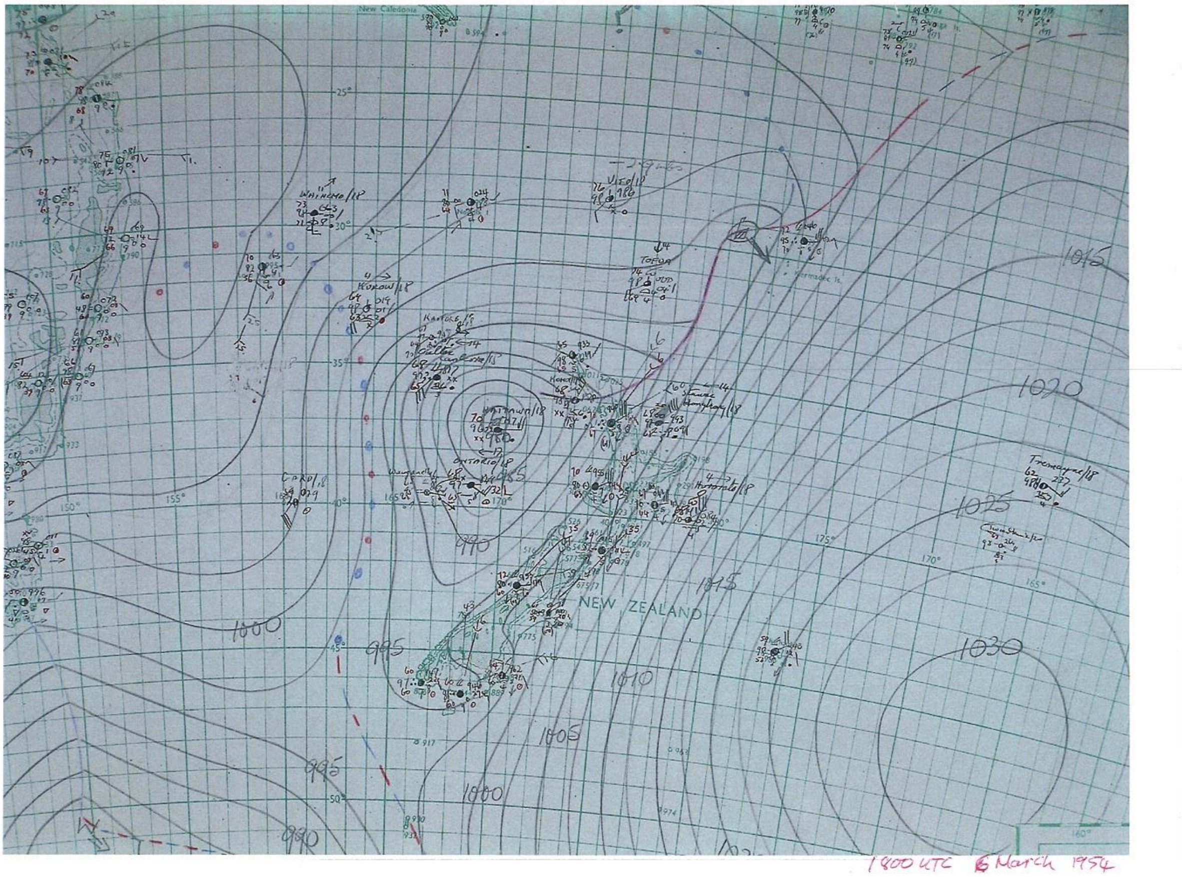

Figure B-1: Weather map 18:00 UTC 6 March 1954.

Appendix C Historical annual maxima from previous studies

Table C-1: Historical annual maxima from sea-level gauges. This table is adapted from Appendix C of T&T (1999), compiled by Peter Blackwood. Only measured data are included (i.e., the maxima estimated by T&T are removed), and the outlying values for Mount Maunganui in 1977 and 1988 were removed by our quality control (e.g., the stilling well was silted up and all data from 1977 is corrupt). Data for Sulphur Point was obtained from Dr Willem de Lange at the University of Waikato.

Year	Moturiki		Mount Maunganui		Tauranga		Sulphur Point	
	Date	Level	Date	Level	Date	Level	Date, time	Level
1960							15-May, 23:33	1.23
1961							17-Jan, 07:42	1.33
1962			1-Jun	1.3	1-Jun	1.48	1-Jun, 05:45	1.48
1963			1-Apr	1.17	1-Apr	1.4	1-Apr, 00:45	1.40
1964					12-Jul	1.31	12-Jul, 22:21	1.31
1965			20-Jan	1.21	20-Jan,29 Jul	1.29	29-Jul, 20:30	1.29
1966					19-Jul	1.42	19-Jul, 21:00	1.42
1967			9-Sep	1.14	26-Apr	1.27	3-Feb, 01:42	1.25
1968			10-Apr	1.4	10-Apr	1.59	10-Apr, 04:20	1.59
1969			7-May	1.14	7-May	1.23	7-May, 11:45	1.23
1970			21-Aug	1.32	21-Aug	1.41	21-Aug, 23:17	1.41
1971	26-Jul	1.29	4-Jan	1.26	4-Jan	1.31	4-Jan, 13:18	1.31
1972	16-Apr	1.32	15-May	1.25	16-Apr	1.41	16-Apr, 22:07	1.41
1973	16-Nov	1.22	16-Nov	1.17	5-Apr,15&16-Nov	1.25	5-Apr, 21:13	1.25
1974	12-Jan	1.28	17-Aug	1.18	12-Jan*	1.32	12-Jan, 00:00	1.32
1975	14-Jun	1.44	14-Jun	1.37	14-Jun	1.4	14-Jun, 23:17	1.40
1976	18-Apr	1.29	18-Apr	1.17	18-Apr	1.25	18-Apr, 22:52	1.25
1977	20-Jul		8-Apr	1.15	8-Apr	1.24	23-Jan, 00:00	1.17
1978	20-Jul	1.45	20-Jul	1.37	20-Jul	1.42	19-Jul, 18:54	1.42
1979	10-Aug	1.24	9-Aug	1.16	9-Aug	1.18	13-May, 20:47	1.11
1980	15-Mar		15-Mar	1.27	15-Mar	1.29	15-Mar, 17:57	1.29
1981	6-Jun	1.29	6-Jun	1.23	*	1.18	14-Apr, 03:14	1.18
1982	23-Jun	1.25	23-Jun	1.17	22&23-Jun	1.21	9-Apr, 20:37	1.22
1983	13-Jul	1.17	22-Dec	1.09	13-Jul,10-Sep	1.14	10-Jul, 06:33	1.04
1984	27-Sep	1.3	27-Sep	1.19	27-Sep	1.24	27-Sep, 21:20	1.24
1985	9-Feb	1.22	23-Jun	1.13				
1986	26-May	1.37						
1987	14-Jul	1.34	14-Jul	1.07				
1988	20-Feb	1.23					30-Sep, 23:20	1.10

Year	Moturiki		Mount Maunganui		Tauranga		Sulphur Point	
1989	8-Apr	1.27	9-Apr	1.22			18-Oct, 09:55	1.25
1990	28-Apr	1.26	25-Apr	1.31			12-Aug, 10:50	1.23
1991	15-Jun	1.38	15-Jun	1.33			15-Jun, 22:15	1.40
1992	21-Feb	1.23	7-Jun	1.18			6-Jun, 23:50	1.33
1993	19-Sep	1.2	19-Sep	1.11			19-Sep, 21:35	1.23
1994	2-Mar	1.21	2-Mar	1.12			2-Mar, 10:40	1.21
1995	14-Jul	1.39	14-Jul	1.26			2-Jul, 22:05	1.11
1996			2-Aug	1.34			2-Aug, 21:50	1.33
1997			11-Jan	1.2			11-Jan, 09:00	1.23
1998							14-Jul, 23:25	1.25

Appendix D Annual mean sea level data

Table D-1: Annual mean sea level data. MSL specified in metres relative to MVD–53.

Year	Moturiki	Tug Berth	Tug Berth Adjusted	Hairini	Hairini Adjusted	Oruamatua	Kotuku
1973	0.04						
1974	0.09						
1975	0.08						
1976	0.06						
1977	0.03						
1978	0.03						
1979	0.04						
1980	0.05						
1981	0.05						
1982	0.05						
1983	0.02						
1984	0.04						
1985	0.08						
1986	0.08						
1987	0.02						
1988	0.03						
1989	0.10						
1990	0.08	0.10	0.10				
1991	0.07	0.07	0.07				
1992	0.05	0.07	0.06				
1993	0.00	0.00	-0.01				
1994	0.02	-0.01	-0.03				
1995	0.04	0.01	-0.01				
1996	0.07	0.06	0.04				
1997	0.05	0.03	0.01				
1998	0.06	0.07	0.05				
1999	0.12	0.12	0.09				
2000	0.12	0.14	0.11				
2001	0.12						0.10
2002	0.09					0.17	0.07
2003	0.10	0.10	0.06	0.15	0.15	0.16	0.08
2004	0.08	0.09	0.04	0.12	0.12	0.14	0.06
2005	0.09	0.10	0.05	0.15	0.14	0.17	0.07
2006	0.09	0.09	0.04	0.14	0.13		0.06

Year	Moturiki	Tug Berth	Tug Berth Adjusted	Hairini	Hairini Adjusted	Oruamatua	Kotuku
2007	0.08	0.11	0.06	0.14	0.12	0.15	0.06
2008	0.11	0.14	0.08	0.16	0.14	0.23	0.09
2009	0.10	0.16	0.10	0.18	0.15	0.15	0.09
2010	0.08	0.14	0.07	0.15	0.13	0.13	0.06
2011	0.11	0.17	0.10	0.19	0.16	0.19	0.09
2012	0.12	0.19	0.11	0.19	0.16	0.26	0.10
2013	0.14	0.17	0.09	0.21	0.17	0.13	0.12
2014	0.14	0.12	0.04	0.19	0.15	0.12	
2015	0.15	0.17	0.08	0.20	0.15	0.14	
2016	0.16	0.18	0.10	0.23	0.18	0.15	