The effect of sea-level rise on the frequency of extreme sea levels in New Zealand

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Executive summary

The Parliamentary Commissioner for the Environment contracted NIWA to calculate the changing likelihood of occurrence (frequency or return period) of extreme sea-levels in New Zealand due to sea-level rise (SLR).

The effects of historical SLR were investigated, along with the four median future SLR projection trajectories from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

The purpose of this report is to document the methods used for the sea-level exceedance calculations, present results, and make general conclusions about the effect of SLR on extreme sea-level frequency. NIWA supplied Parliamentary Commissioner for the Environment with tables of the percent of high waters exceeding high sea-level thresholds, in digital format.

Sea-level records at the ports in Auckland (Waitemata Harbour), Wellington, Lyttelton and Dunedin (Otago Harbour) were quality checked and used to calculate the likelihood of extreme sea levels being reached.

Historically, SLR since 1900 has caused an approximately linear increase in the frequency of high waters reaching the mean high-water perigean-springs elevation. This had led to an approximate doubling, due to historical SLR since 1900, in the number of days when tides reach the mean high-water perigean springs elevation, which is used as a "red-alert" level in New Zealand to warn of increased potential for coastal inundation.[1] SLR since 1900 has caused a more rapid, approximately quadratic, increase in the frequency of high waters reaching the present-day highest astronomical tide elevation or higher, a result that is consistent with international studies. In other words, there is a non-linear relationship between the rate of SLR and the increase in frequency of extreme sea-levels being reached – the frequency will rise increasingly fast as sea level rises.

Sites with small tidal range, such as Wellington, are more sensitive to SLR. They will experience a greater increase in the number of high waters reaching present-day extreme sea levels than sites with large tidal range such as Auckland. The reason for this is that the tide constitutes most of the sea-level variability in New Zealand (even at the sites with small tides, like Wellington). Thus, extreme sea-levels peak at or close to high tide and the tide makes up a large fraction of the total sea level. Where tides are small, SLR forms a greater proportion of the tide than sites with larger tide ranges, and therefore the total sea-level height.

The 0.01 annual exceedance probability (AEP) sea-level elevation is often adopted as a design "extreme sea-level" for coastal-hazard planning in New Zealand, being a high sea level that is exceeded infrequently when high tides and storm surges combine (i.e., a storm tide). This high storm-tide sea-level elevation is seldom reached in any given year at present-day mean sea level (1% chance), however, projected SLR will noticeably increase the frequency of sea-levels reaching or exceeding these elevations.

Present-day 0.01 AEP sea levels are expected to be reached or exceeded at least once every year (on average) after a SLR of only 0.16 m at Wellington, and after a SLR of 0.33 m at Auckland. In other words, extreme sea-levels that are expected to be reached or exceeded only once every 100 years (on average) at present-day MSL, will occur at least once per year or more (on average), at all sites, after only a 0.33 m SLR relative to present-day MSL.

[1] https://www.niwa.co.nz/our-science/coasts/tools-and-resources/tide-resources

A 0.33 m SLR is expected by 2070 under the "business as usual" IPCC RCP8.5 median SLR trajectory, or by 2090 under the low-emissions RCP2.6 median trajectory. Therefore, by 2050–2070, depending on location, there will be around one event or more per year that reaches what is presently considered to be an extreme 0.01 AEP sea level, and this will occur for either the fastest *or slowest* IPCC AR5 median SLR trajectories (with the exception of sites with large tidal range such as Auckland, when this might be delayed until 2090 if SLR proceeds slowly).

Once this annual occurrence threshold is reached, the number of sea levels exceeding the present-day 0.01 AEP elevation will increase rapidly in time. For example, SLR of 1 m is considered appropriate for coastal hazard planning purposes over a 100-year timeframe in New Zealand. There will be hundreds of occurrences per year of the present-day 0.01 AEP extreme sea level, at all sites, if SLR reaches 1 m relative to present-day MSL, with all (100%) high tides in Wellington exceeding this level.

Aside from "extreme sea levels", so-called "lesser extremes", or "nuisance flooding" events that occur about once per year at present-day MSL will occur about 10-times per year by about 2045, and will increase rapidly in frequency over time thereafter.

This report focuses on the *increasing frequency* of sea-levels reaching or exceeding high thresholds relative to present-day mean sea level, using some historic events as examples. In addition, future SLR will *increase* the *depth* of large storm tides (extreme sea levels). Inundation during future infrequent extreme sea level events will be deeper and will reach further inland than at present.

1 Introduction

Coastal erosion and inundation are natural processes that help shape the character of the coastline around New Zealand. Most coastal hazard problems have been caused by coastal development and subdivision being located too close to the existing shoreline to accommodate natural changes and trends in shoreline movements (MfE 2008).

Tsunami and land subsidence aside, there are several meteorological and astronomical influences on sea-level that can combine in a number of ways to inundate low-lying coastal areas or erode coastal sediments: the height of mean-sea level (MSL) relative to a local datum or landmark, astronomical tides, synoptic weather-induced storm-surge, wave set-up and run-up, sea-level anomaly (SLA) caused by seasonal, inter-annual and inter-decadal climate variability, and long-term change in MSL through sea-level rise (SLR) (Stephens et al. 2014). *Storm tide* is defined as the sea-level peak reached at or close to high tide during a storm event, resulting from a combination of SLA + tide + storm surge. Since the tide is the dominant cause of sea-level variability in New Zealand (notwithstanding wave setup and runup in some locations), storm tides peak close to the predicted high tide, even during storms. The sea-level record can be sampled to obtain the *high-water* peaks that occur at or close to high tide when exposure to inundation is greatest. The distribution of *high-water* peaks is useful to examine the exposure to inundation because it includes the various coincident combinations of tide, SLA and storm surge, some of which will result in large and relatively infrequent "extreme" storm tides. There are about 706 high-water peaks per year in New Zealand, as a result of the semi-diurnal tidal regime that is dominated by the M_2 twice-daily lunar tide which has a period of 12.42 hours.

Climate change will not introduce any new types of coastal hazards, but it will affect existing coastal hazards by changing some of the hazard drivers. Climate change (in the form of SLR, or changes in wave and storm surge characteristics) will exacerbate coastal erosion and inundation in many parts of the New Zealand coast, further increasing the impacts of coastal hazards on coastal development from now on (MfE 2008).

As relative SLR[2] increases MSL, there is naturally an increase in tidal elevations (e.g., mean high-water springs, MHWS; mean low water springs, MLWS; etc.). Typically MHWS is used to delineate the land-sea interface and a baseline for inundation thresholds. Direct consequences of rising sea level, relative to a previously-fixed coastal survey datum used for past coastal development and infrastructure, will include increased spatial and temporal inundation during extreme events. Not only are extreme flooding events reaching higher grounds and covering larger areas due to relative SLR, the frequency and duration of these extreme flood events are increasing (Sweet et al. 2014; Sweet and Park 2014). This was also the conclusion reached by the Australasian chapter of the IPCC Working Group II Fifth Assessment Report (Reisinger et al. 2014), who stated for our region that 'projected mean SLR will lead to large increases in the frequency of extreme sea level events (*very high confidence*), with other changes in storm surges playing a lesser role".

Another consequence of relative SLR is the increase in *lesser extremes* such as occasional minor coastal flooding experienced during normal higher high tides. These events are becoming more noticeable and widespread along many U.S. coastal regions and are today becoming more of a nuisance (Sweet and Park 2014). As sea levels continue to rise and with an anticipated acceleration in

[2] *Relative* sea level is the sea level related to the level of the land. *Relative* sea level changes can thus be caused by absolute changes of the sea level and/or by absolute movements of the land. It is local *relative* SLR that needs to be adapted to at a specific location.

the rate of rise from ocean warming and loss of land-ice, concern exists as to when more substantive impacts from tidal flooding of greater frequency and duration will regularly occur (Sweet et al. 2014).

In 2014, the Parliamentary Commissioner for the Environment (PCE) published the report "Changing climate and rising seas: Understanding the science" (PCE 2014), which included the paragraph "The National Institute of Water and Atmospheric Research (NIWA) has projected that in 30 years' time, this level of flooding [*the flooding experienced during the 23 January 2011 storm tide, which had an annual exceedance probability of about 1%*] in Auckland will occur about once every ten years. A few decades later, such flooding is expected to occur every year if the world takes no action to reduce greenhouse gas emissions". Note that this paragraph was based on calculations undertaken using sea-level measurements at Auckland, and on the highest "business as usual" SLR trajectory RCP8.5 from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Church et al. 2013b).

PCE subsequently contracted NIWA to collate and quality-check New Zealand's four longest sea-level records at Auckland, Wellington, Lyttelton and Dunedin, and to use them to estimate the likelihood of occurrence (frequency) of extreme sea levels, including some historical sea-inundation events with reported coastal hazard impacts. NIWA was requested to calculate the expected change in frequency of occurrence of extreme sea levels due to SLR, using the median of the four SLR projection trajectories from the IPCC AR5 report (Church et al. 2013b). NIWA was contracted to supply PCE with tables showing the changing likelihood of occurrence (frequency or return period) of extreme sea-levels in New Zealand due to SLR, and to draw out general conclusions.

Extremes are generally described by exceedance events which are events which occur when some variable exceeds a given level (Hunter 2012). Two statistics are conventionally used to describe the likelihood of extreme events such as flooding from the ocean. These are the *average recurrence interval* or *ARI*, and the exceedance probability (P) for a given period (T). The ARI is the average period between extreme events (observed over a long period with many events), while the exceedance probability is the probability of at least one exceedance event happening during the period T (Hunter 2012). If $T = 1$ year, then P is equivalent to the annual exceedance probability (*AEP*). For ARI ≥ 10 years, AEP ≈ 1/ARI. Both ARI (in years) and AEP (chance per year on a 0–1 scale) are used in this report.

The primary purpose of this report is to document the methods used for the sea-level exceedance calculations, present basic analyses to illustrate how the methods were applied, and make general conclusions about the effect of SLR on extreme sea-level frequency.

2 Methods

2.1 Overview of methods

This section summarises the methods used in the study. More detail is provided later in the report.

All analyses in this report are based on sea-level measurement records from the Ports of Auckland, Wellington, Lyttelton and Dunedin. These are the longest sea-level records in New Zealand. The following steps summarise the methods used:

1. Sea-level measurement records from the Ports of Auckland, Wellington, Lyttelton and Dunedin were used in this study (Table 2-1). Hourly sea-level data was obtained from Emeritus Professor John Hannah (formerly at the School of Surveying, University of Otago). Professor Hannah’s data was originally sourced from Land information New Zealand (LINZ) records (Hannah 2015). Professor Hannah also supplied monthly mean sea levels at each location, which he had adjusted to a common local vertical datum, and used in several published studies documenting historical MSL trends in New Zealand (Hannah 1990; Hannah 2004; Hannah 2015; Hannah and Bell 2012).

2. The sea-level records were used for two purposes: 1. calculating high-tide and extreme sea-level elevations (Section 2.4), and 2. calculating the frequency of sea levels that exceed high elevations (Section 2.5).

3. Monthly MSL were calculated from the hourly data, and were compared with those supplied by Professor Hannah. The comparison showed where datum shifts were required to adjust the hourly dataset to the same common datum. The adjustments or offsets applied are explained in Section 2.2.

4. At each location the annual maxima were quality checked for the entire record. The annual maxima were used to model the frequency–magnitude distribution of extreme sea-levels, as described in 2.4.1. The extreme sea-level analyses provide extreme sea-level heights, and their expected occurrence frequency relative to a zero MSL, which can be adjusted to present-day (or historical) MSL.

5. A careful quality check was made of the most recent 19 years of hourly sea-level data at each location. The quality check is described in Section 2.2.1. A 19-year measurement period contains a complete nodal tide cycle, which arises from variations in the lunar declination over an 18.6-year period (Pugh 2004). Thus a 19-year measurement period fully represents tidal variability due to astronomical gravitational forcing. 19 years of data is considered sufficient to define the non-extreme body of the empirical sea-level distribution; considerably more effort would be required to quality check every hourly data point for the entire sea-level record.

6. A tidal harmonic analysis of the 19-year records was undertaken following the method of Foreman et al. (2009). The harmonic analysis was used to calculate the height of mean high-water perigean springs (MHWPS), which is the sum of the amplitudes of the three largest tidal harmonics: M2 (principal lunar semi-diurnal) + S2 (principal solar semi-diurnal) + N2 (larger lunar elliptic semi-diurnal). About 6–10% of all high tides exceed the MHWPS amplitude in New Zealand, depending on location. The harmonic analysis was also used to calculate the height of highest astronomical tide (HAT), which is the highest tide expected during an 18.6-year long nodal tide cycle.

7. The 19 years of recent quality-checked data were used to represent the empirical (measured) sea-level distribution, which was used to explore the increase in frequency, due to SLR, of sea-levels that reach (what are presently considered to be) extreme sea levels (or high high-tide levels, e.g., MHWPS or HAT). The method of determining SLR effects on sea-level exceedance frequency is described in Section 2.5.

8. SLR projection trajectories for future greenhouse gas emission scenarios were obtained from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Church et al. 2013b).

9. Damaging storm-related coastal inundation events were identified and their likelihood of occurrence at present-day MSL was estimated. The effect of SLR on the future frequency of similar such events was investigated.

2.2 Sea-level data and local vertical datum

All of the analyses in this report use sea-level height data relative to a common local vertical datum. This section documents the conversion of data from gauge zero to the local vertical datum commonly used in the region, including any required datum shifts.

The work uses hourly data supplied by Professor Hannah, which was originally sourced from LINZ or the University of Hawaii Sea-level Center. The hourly data formed the basis for Professor Hannah's research on sea-level around New Zealand (Hannah 1990; Hannah 2004; Hannah and Bell 2012). Professor Hannah processed the hourly data into daily then monthly then annual means, making any datum adjustments at the monthly and annual level rather than at the hourly level, which is a suitable approach for calculating long-term sea-level change (Hannah 2015). It is easier to adjust the fewer monthly means than the multiplicity of hourly data. In an email dated 4 December 2014, Professor Hannah noted that "Auckland was quite straightforward, but the Wellington data needs to be corrected for a very slow subsidence from about 1945 to 2000, Lyttelton has numerous datum offsets and Dunedin a couple of offsets".

Table 2-1 lists the durations of sea-level measurement records from the Ports of Auckland, Wellington, Lyttelton and Dunedin that were used in this study. Table 2-2 lists the relationship between local vertical datum and chart datum (usually gauge zero), including present-day chart datum and historical chart datum where applicable. Table 2-3 lists the local vertical datums in New Zealand together with the tide gauge data used to define them.

Table 2-1: Duration of hourly sea-level data used in this study. Data source: Prof J. Hannah (from LINZ and University of Hawaii Sea-level Center databases).

Site	Start time	Finish time	Maximum gap length (days)
Auckland	26-Oct-1903 09:00:00	08-Aug-2014 14:00:00	368
Wellington	01-Jan-1944 00:00:00	31-Dec-2013 23:00:00	188
Lyttelton	01-Jan-1924 00:00:00	31-Dec-2012 23:00:00	1402
Dunedin	31-Dec-1899 00:00:00	31-Dec-2013 23:00:00	3717

Table 2-2: Relationship between local vertical datum and chart datum. CD = chart datum, LVD = local vertical datum. Chart datum equals gauge zero for all four ports.

Gauge site	Benchmark Code	Present-day CD below BM (m)	LVD	LVD below BM (m)	LVD above present-day CD or tide gauge zero (m)	LVD above *historic* CD or tide gauge zero (m)
Auckland	DD1N	5.233	Auckland (1946)	3.491	1.742	
Wellington	ABPB	3.002	Wellington (1953)	2.087	0.915	0.595 (1945 chart datum)
Lyttelton	B40V	4.401	Lyttelton (1937)	3.165	1.236	0.913 (1928 chart datum)
Dunedin	AFEQ	3.728	Dunedin (1958)	2.7366	0.9914	

Table 2-3: Local vertical datum's in New Zealand together with the tide gauge data used to define them. Source: Hannah and Bell (2012).

Datum name	Location	Definition	MSL datum defined
Auckland 1946 (AVD-46)	Port of Auckland	MSL from 7 years of TG data collected in 1909, 17–19, 21–23	(1916) 5.72 feet above the 1973 gauge zero
Wellington 1953 (WVD-53)	Port of Wellington	MSL from 14 years of TG data collected between 1909 and 1946	(1927) 1.96 feet above the post-1973 gauge zero
Lyttelton 1937 (LVD-37)	Port of Lyttelton	MSL from 9 years of TG data collected in 1917, 18, 23–27, 30, 33	(1925) 3.07 feet above the 1918 gauge zero
Dunedin 1958 (DVD-58)	Port of Dunedin	MSL from 9 years of TG data collected in 1918, 23–27, 29, 35, 37	(1927) 3.26 feet above the 1980 gauge zero

The raw hourly data from Wellington, Lyttelton and Dunedin were adjusted as described by Hannah (2015). NIWA had already previously obtained and adjusted the datums for the hourly sea-level record for Auckland.

For Wellington, the monthly MSL are plotted in Figure 2-1, and both the raw and datum-adjusted hourly sea-level data are plotted in Figure 2-2. For Lyttelton the monthly MSL are plotted in Figure 2-3, and both the raw and datum-adjusted hourly sea-level data are plotted in Figure 2-4. Hannah (2015) notes that the Lyttelton data from 2012 onwards show significant and unresolved inconsistencies, therefore we have only used data from Lyttelton to the end of 2011. For Dunedin the monthly MSL are plotted in Figure 2-5, and both the raw and datum-adjusted hourly sea-level data are plotted in Figure 2-6.

The datum-adjusted datasets consisted of hourly data relative to their local vertical datums (Table 2-3). Figure 2-7 plots the hourly sea-level time-series datasets at each site, relative to the respective local vertical datums. The different tide ranges at each site are obvious in Figure 2-7.

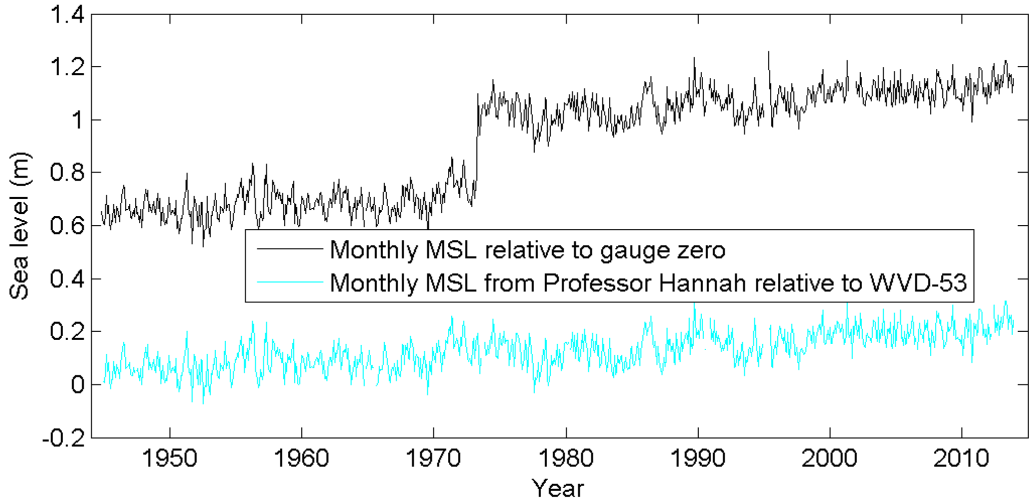

Figure 2-1: Monthly MSL at Wellington. Monthly MSL calculated from the hourly sea-level data is compared to the monthly means obtained from Professor Hannah. The monthly MSL data were supplied relative to a gauge zero of 0.595 m below WVD–53, which was 1945 chart datum. Professor Hannah's data has been offset by -0.595 m before plotting so that it is relative to WVD-53. Hourly data before May 1973 were supplied relative to 1945 chart datum. Present-day gauge zero (chart datum) is 0.915 m below WVD–53. Hourly data from May 1973 onward were supplied relative to present-day chart datum.

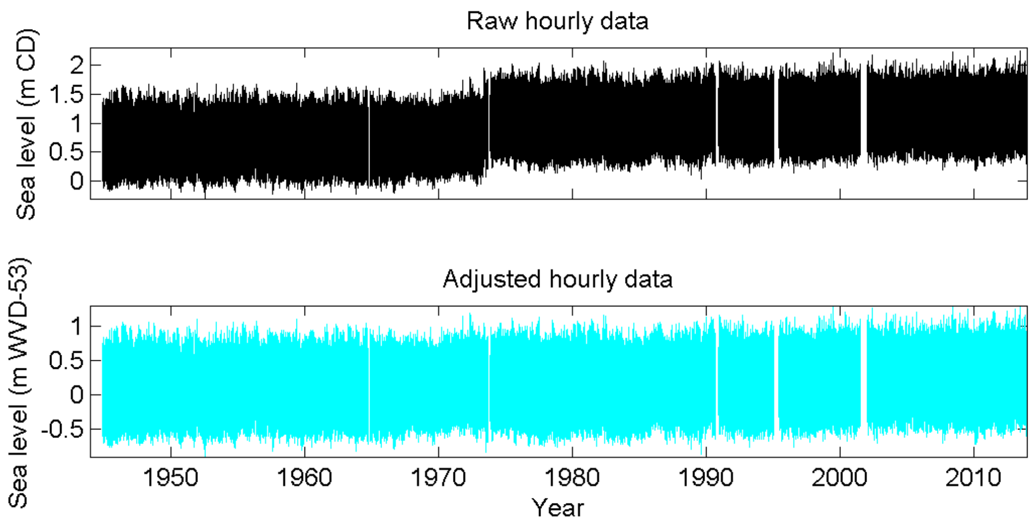

Figure 2-2: Raw and datum-adjusted hourly data from Wellington.

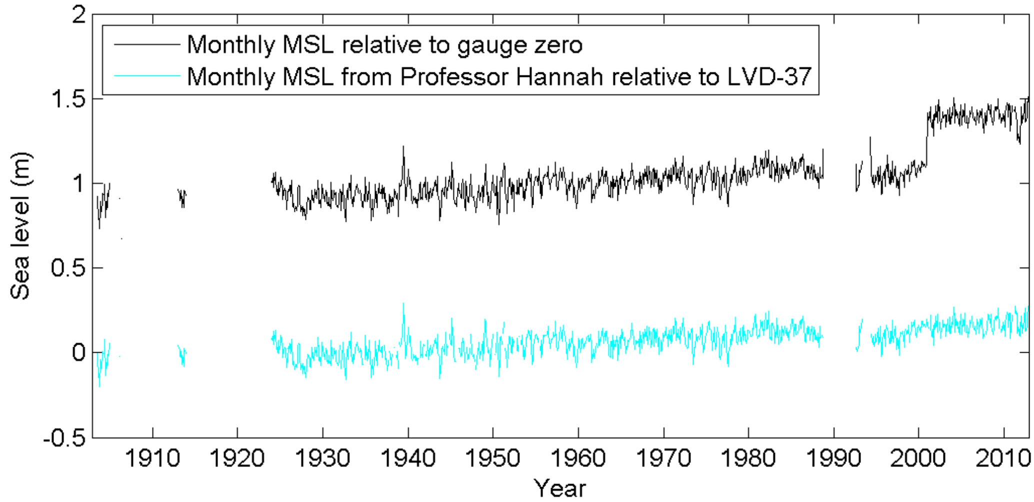

Figure 2-3: Monthly MSL at Lyttelton. Monthly MSL calculated from the raw hourly sea-level data is compared to the monthly means obtained from Professor Hannah. The monthly MSL data is plotted as supplied relative to gauge zero, whereas Professor Hannah's data is shown relative to LVD–37.

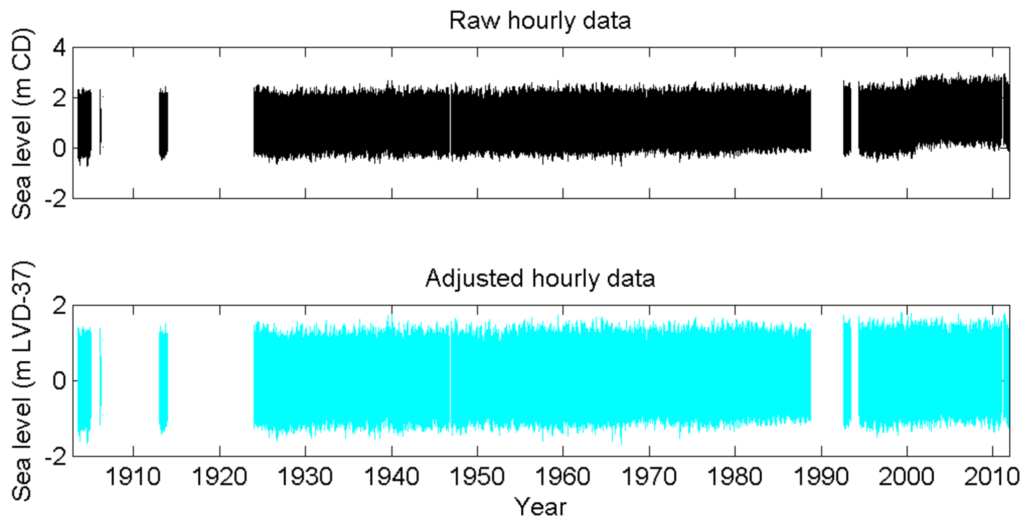

Figure 2-4: Hourly data at Lyttelton used for the study. Raw hourly data is shown relative to chart datum (CD), which equals gauge zero. The adjusted hourly data are plotted relative to LVD–37.

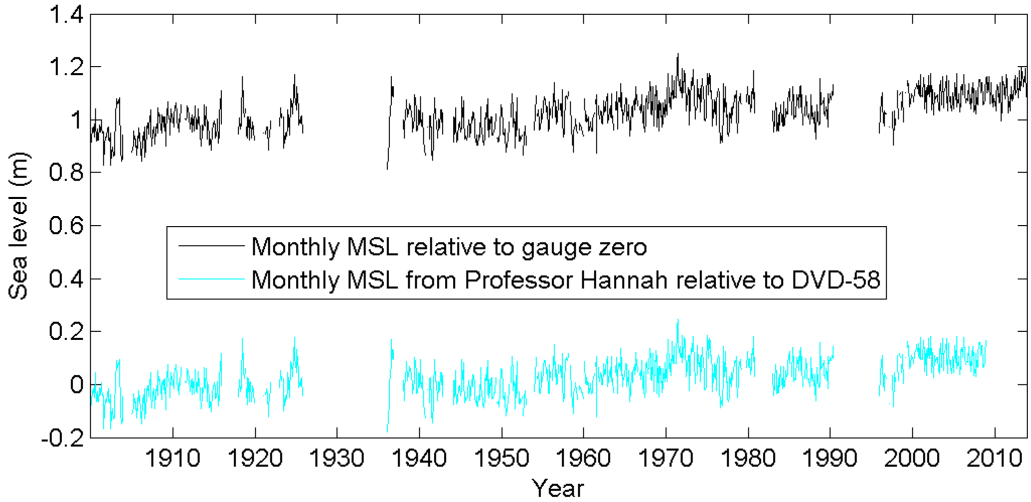

Figure 2-5: Monthly MSL at Dunedin. Monthly MSL calculated from the raw hourly sea-level data is compared to the monthly means obtained from Professor Hannah. The monthly MSL data is plotted relative to gauge zero (as supplied), whereas Professor Hannah's data is shown relative to DVD–58.

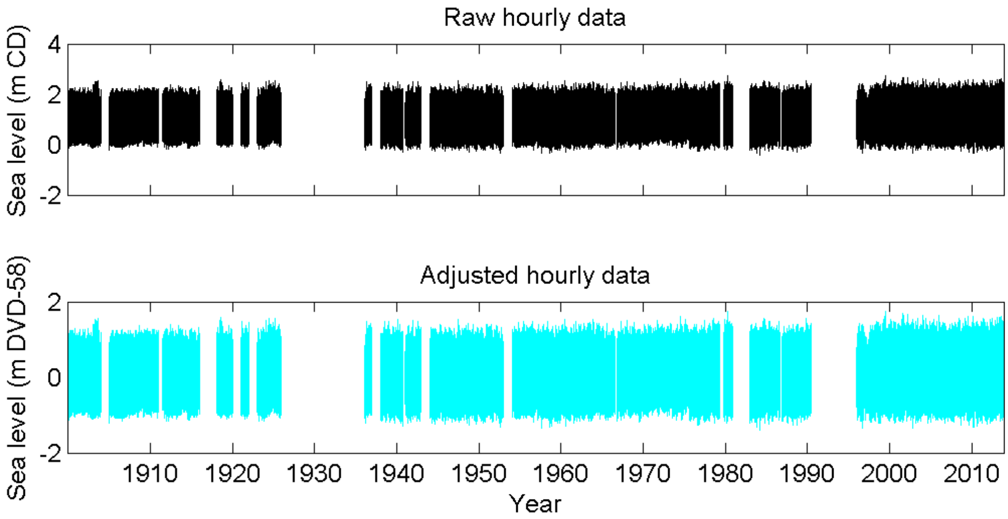

Figure 2-6: Hourly data at Dunedin used for the study. Raw hourly data is shown relative to chart datum (CD), which equals gauge zero. The adjusted hourly data are plotted relative to DVD–58.

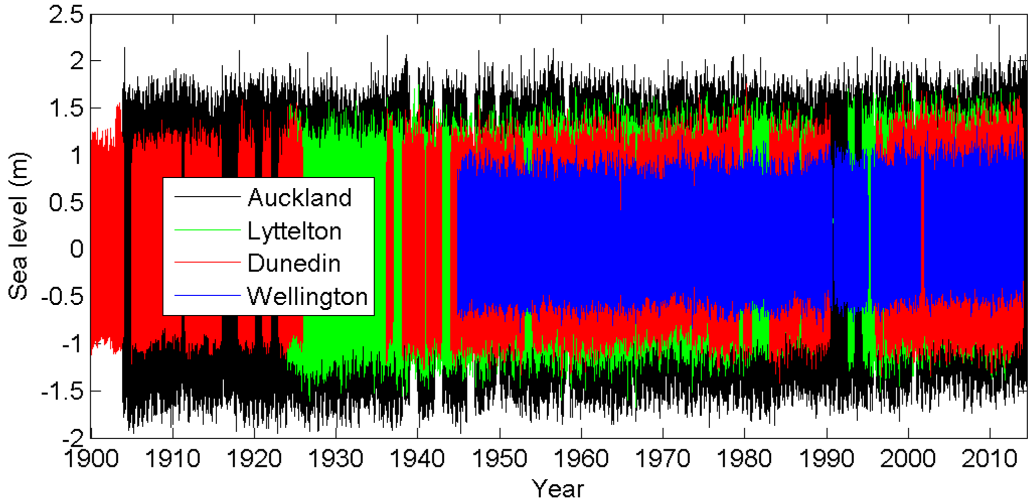

Figure 2-7: Quality-assured hourly sea-level data. Sea level at each site is presented relative to its respective local vertical datum. Note: the different tide ranges apply to each location.

2.2.1 Hourly sea level quality analysis

Following the processing of the data at each location to a common datum across the entire record, a careful quality check was made of the most recent 19 years of hourly sea-level data. The 19-year records were used to represent the empirical (measured) sea-level distribution in subsequent analyses.

The data were inspected visually against predicted tides and obvious errors such as data spikes and time shifts were replaced. Spikes were identified as large jumps in the non-tidal residual, which were inconsistent with storm surge or high frequency wave events such as tsunami. De-spiking was applied to individual hourly data points and were replaced using linear interpolation between neighbouring points.

2.3 Sea-level rise

Historical rates of linear SLR were calculated for the four locations by Hannah and Bell (2012), and these are shown in Table 2-4. The average for New Zealand is 1.7 mm yr^{-1} (Hannah and Bell 2012), which is close to the average rate of rise globally over the past century (Church et al. 2013b), which means that global-average SLR projections can be readily downscaled to the New Zealand region.[3]

Table 2-4: Historical relative sea-level rise rates. Source: Hannah and Bell (2012). The SLR rates are relative to the local landmass at the sea-level gauge locations (and implicitly include vertical landmass movement).

Location	Historical rate of sea-level rise (mm yr^{-1})
Auckland	1.5 ± 0.1
Wellington	2.0 ± 0.2
Lyttelton	1.9 ± 0.1
Dunedin	1.3 ± 0.1

[3] Note: Ackerley et al. (2013) showed that for NZ region, there is likely to be a small increase of 0.01–0.05 m in SLR projections relative to the global mean.

SLR projections for future greenhouse gas emission scenarios (Representative Concentration Pathways or RCPs) were included in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Church et al. 2013b). These were digitised from Figure 13.11a of Church et al. (2013b), and are plotted in Figure 2-8 relative to a zero baseline of the average MSL for the period 1986–2005. An offset of 0.06 m was subtracted from the median of the SLR projection trajectories in Figure 2-8 to move the zero baseline to 2015 as listed in in Table 2-5. These values for SLR were used in Section 2.5 to estimate the future change beyond present (2015) in the number of exceedances of high storm-tide levels.

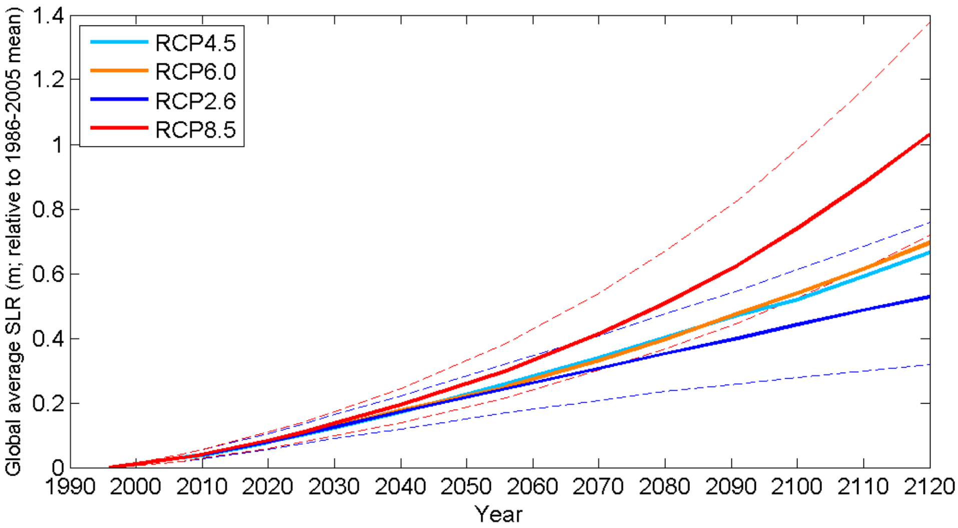

Figure 2-8: Global-average sea-level rise projection trajectories, digitised from Figure 13.11a of Church et al. (2013b). The solid lines represent the median SLR trajectories, while the dashed lines show the likely range, based on one standard deviation about the median (Church et al. 2013a) (for clarity only the lowest RCP2.6 and highest RCP8.5 emissions pathways standard-deviation bounds are shown).

Table 2-5: Median global-average sea-level rise projection trajectories, digitised from Figure 13.11a of Church et al. (2013b). MSL are presented relative to MSL = 0 in 2015. A vertical offset of 0.06 m was applied to adjust the baseline for the SLR trajectories from 1986-2005 to 2015.

Year	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	0.00	0.00	0.00	0.00
2020	0.02	0.02	0.02	0.02
2025	0.04	0.04	0.04	0.05
2030	0.06	0.06	0.07	0.07
2040	0.11	0.11	0.11	0.13
2056	0.18	0.20	0.19	0.24
2070	0.25	0.28	0.27	0.35
2080	0.29	0.34	0.34	0.45
2091	0.34	0.41	0.41	0.56
2100	0.38	0.46	0.48	0.68
2110	0.43	0.53	0.55	0.82
2120	0.47	0.61	0.63	0.97

2.4 Extreme sea level and damaging historical events

This section documents temporarily high sea levels (during storms or king tides) that have been measured historically and which had notable impacts, and puts them in context of their expected frequency of occurrence relative to the existing period of sea-level measurement. Section 2.5 then investigates how SLR is expected to change the frequency of occurrence of these events.

Table A-1 lists *measured* extreme sea-level elevations during recent storm events, along with links to their description. When predicting the height of extreme sea levels, it is common to treat the gravity-wave-induced setup and runup separately from the still (non-wave) water level (i.e., MSL + SLA + tide + storm surge) because sea-level gauges, such as the ones used in this study, are usually placed inside harbours to minimize the effects of wave setup and runup (Stephens et al. 2014). Thus, these port sea-level records cannot be used to estimate the probability of occurrence of wave-related flooding or erosion. Therefore, in selecting the historical high sea-level events within Table A-1, care was taken to choose events that were dominated by storm tide rather than waves.

The highest sea-level on record at the Port of Auckland occurred on 23 January 2011. A low-pressure system coincided with a very high tide. The predicted tide was 1.71 m, which is above the 1.55 m MHWPS tide elevation (HAT = 1.91 m), and at approximately the 99th percentile of all high tide peaks. A storm surge of 0.41 m coincided with high tide at the port of Auckland. The 0.41 m storm surge was approximately a 99th percentile of recorded storm surge peaks. The event coincided with a background SLA of nearly 0.1 m (25% of the storm-surge). MSL at the time was 0.15 m above AVD-46. The weather associated with this event was not particularly remarkable, but the coincidence of the storm surge with a very high tide and high SLA resulted in the highest sea-level on record, and caused considerable inundation, closed motorways and flooded coastal property, with considerable damage (total of $7M in insured losses[4]). The AEP of this event was estimated between 0.005–0.011 (Table A-1).

The highest sea-level on record at the Port of Wellington occurred on 7 June 2008, when Wellington was hit by strong southerlies and driving rain on the evening of the 7th. High winds in the Wellington hills dropped back to about 100 km/hr on the afternoon of the 7th. Wellington harbour was reported to be rough and boisterous. The weather event created a storm surge of 0.23 m that coincided with a high spring tide of 0.74 m, which is about the 99th percentile of all high tides. The sea-level reached 1.31 m WVD-53 and had an AEP of 0.015 (Table A-1).

The highest sea-level on record at Lyttelton reached 1.80 m LVD–37 on 17 April 1999, having an AEP of 0.021. A 95th percentile high tide combined with a 0.32 m storm surge. The surge was induced by a large storm that covered much of NZ. However, an even larger extreme sea-level was measured at Lyttelton on 27 January 1940, having an AEP of 0.002, but did not reach quite as high since MSL was about 0.11 m lower in 1940. The 1940 event is the highest sea level on record at Lyttelton, once the historical SLR of 0.19 m per century has been removed. The event consisted of a very high 98th percentile tide, plus a 0.16 m surge superimposed on high background sea-level anomaly of 0.1 m.

The 15 June 1999 sea-level is the highest on record at Dunedin. It reached 1.76 m DVD–58 and had an AEP of 0.013. The event consisted of a very high 1.26 m tide, being higher than 99% of all tides, coinciding with a 0.28 m storm surge and a 0.05 m background sea-level anomaly.

[4] http://www.icnz.org.nz/statistics-data/cost-of-disaster-events-in-new-zealand/

Section 3.2 presents results that show the effect of SLR on the likelihood of occurrence (frequency or return period) of the large historical sea-levels discussed above in this section, plus some of the other events listed in Table A-1. For example, sea-levels at Auckland can be expected to reach the same height as the 23 January 2011 storm tide at Auckland approximately once every year by 2070, if SLR follows the RCP8.5 trajectory. Likewise, the 15 June 1999 sea-level at Dunedin would occur approximately 7 times per year under the same SLR scenario.

Table 2-6 shows the *predicted* elevations of high tide and of extreme sea-levels at the four port locations. The high-tide elevations were estimated as described in Section 1, bullet 6. The 1-year ARI sea-level elevation was estimated from the empirical high-water distribution, using Equation 2-3. The 10, 50 and 100-year ARI sea levels were determined using extreme sea-level models, described in Section 2.4.1.

Table 2-6: Predicted high-tide elevations and extreme sea-levels. Sea-levels are presented in metres relative to MSL = 0, i.e., no offset to local vertical datum has been added. MHWPS = mean high-water perigean springs; HAT = highest astronomical tide. ARI = average recurrence interval (years). AEP = annual exceedance probability.

Location	MHWPS	HAT	1-year ARI AEP = 0.63	10-year ARI AEP = 0.1	50-year ARI AEP = 0.02	100-year ARI AEP = 0.01
Auckland	1.55	1.82	1.87	2.03	2.16	2.22
Wellington	0.63	0.77	0.97	1.05	1.10	1.12
Lyttelton	1.12	1.33	1.50	1.60	1.66	1.68
Dunedin	1.09	1.33	1.48	1.62	1.68	1.69

Extremes are generally described by exceedance events which are events which occur when some variable exceeds a given level or threshold (Hunter 2012). Two statistics are conventionally used to describe the likelihood of extreme events such as inundation from coastal or harbour waters. These are the *average recurrence interval* or *ARI*, and the exceedance probability (*P*) for a given period (*T*). The ARI is the average period between extreme events (that would be observed over a very long period with many events), while the exceedance probability is the probability of at least one exceedance event happening during the period *T* (Hunter 2012). These statistics are related by Equation 2-1 (Pugh 1987). If *T* = 1 year (i.e., an annual period), then *P* is equivalent to the annual exceedance probability (*AEP*).

Equation 2-1: Relationship between average recurrence interval (ARI) and probability of exceedance over a given time period. *P* = *AEP* if *T* = 1 year.

$$P = 1 - \exp\left(-\frac{T}{ARI}\right)$$

Hunter (2012) argues that for risk assessment, an estimate of the expected number of exceedances, *N*, is generally more useful than knowing only *P*, which is the probability of *one or more events* occurring. In that case the average, or expected, number of exceedances during the period *T* is given by Equation 2-2.

Equation 2-2: Relationship between average recurrence interval and expected number of exceedances in period *T*.

$$N = \frac{T}{ARI}$$

When using empirical cumulative density functions (CDF) an additional conversion is required to convert between the empirical probability and ARI, knowing the sampling rate S_y of the data (Equation 2-3). There are 706 high tides (and hence potential storm-tide inundation occurrences) per year, so S_y = 706 when working with just high-water data. There are 8766 hourly records per year, so S_y = 8766 when working with hourly data.

Equation 2-3: Equation used to convert empirical CDF probability into ARI. S_y = sampling rate (per year). P_e = empirical probability.

$$ARI = \frac{1}{S_y\left(1 - P_e\right)}$$

Equation 2-4: Conversion from expected number of exceedances in period *T* to percentage of all high waters. For high water S_y = 706.

$$PC_{HW/yr}(\%) = \frac{N}{S_y T} \cdot 100$$

2.4.1 Calculating extreme sea level

Extreme-value models were used to estimate the frequency–magnitude distribution of extreme sea levels.

A previously-calculated extreme sea-level distribution (Stephens et al. 2013) was used for the port at Auckland (Figure 2-9), which was based on the Monte Carlo joint-probability method (Goring et al. 2011). Extreme sea-level distributions at Wellington, Lyttelton and Dunedin were calculated using a generalised extreme-value (GEV) distribution fit to annual maxima (AM), which is simple to apply. This is a robust method for environmental records containing greater than about 50 annual maxima (i.e., >50 years data) (Coles 2001), and it is simple to apply because only annual maxima are required, which removes the requirement to quality check all data points within long sea-level records. Stephens et al. (2013) showed that at Auckland, the AM/GEV method produced similar results to the joint-probability method of Goring et al. (2011) as expected for long records, Figure 2-9.

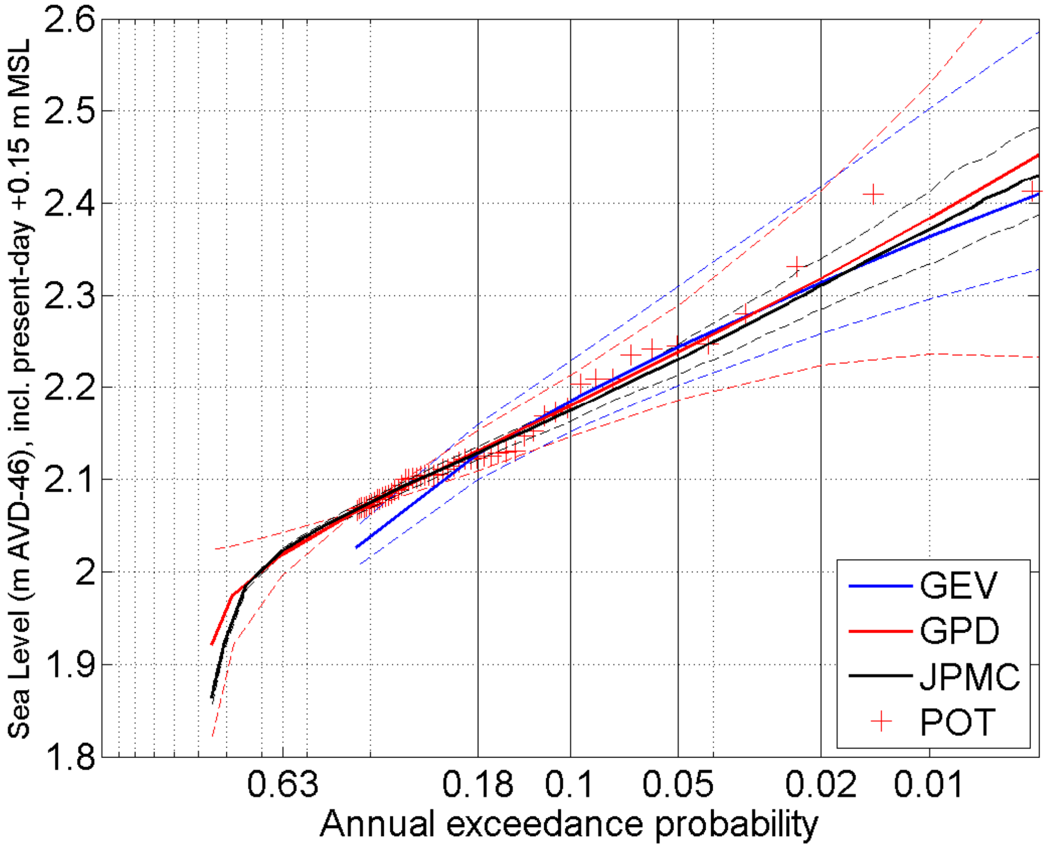

Figure 2-9: Extreme sea-level curves using Port of Auckland tide-gauge data. Three techniques were used: the Monte-Carlo joint-probability technique (MCJP), generalised Pareto distribution (GPD) fitted to peaks-over-threshold (POT) data and generalised extreme-value distribution (GEV) fitted to annual maxima (AM). Bold lines indicate central fit, dashed lines indicate 95% confidence intervals. The POT data have also been plotted using Gringorten (1963) plotting positions. Elevations are relative to AVD-46 including +0.15 m offset for baseline mean sea level (present-day estimate). The GPD method is not used in this report.

2.5 Calculating sea-level rise effects on the frequency of extreme sea level

SLR over the last century has already increased the frequency of sea levels reaching a particular fixed elevation (e.g., beach berm or seawall level). As sea level continues to rise over the coming centuries, extreme sea level events will reach higher than they did before. Sea-levels that have been reached or exceeded infrequently at present-day sea level (or lower), and which are presently considered to be extreme, will occur more often after a period of further SLR. Future SLR will cause less-extreme sea-levels to reach elevations that are presently only reached during the highest combinations of tides and storm surges.

Extreme sea-level elevations (Table 2-6) and the elevations of high measured sea-levels (Table A-1) were presented in Section 2.4.

This section estimates the increase in the frequency of these extreme sea levels, due to SLR.

The process is illustrated in Figure 2-10, which plots both the extreme and empirical (measured) sea-level distributions at Auckland. 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 horizontal dashed line shows the present-day AEP = 0.01 (or 1%) extreme sea level. The vertical dashed lines mark the expected change in the annual exceedance probability, based on the intersection of the present-day 0.01 AEP sea level with the expected sea-level distribution following 0.3, 0.5 and 1.0 m sea-level rise.

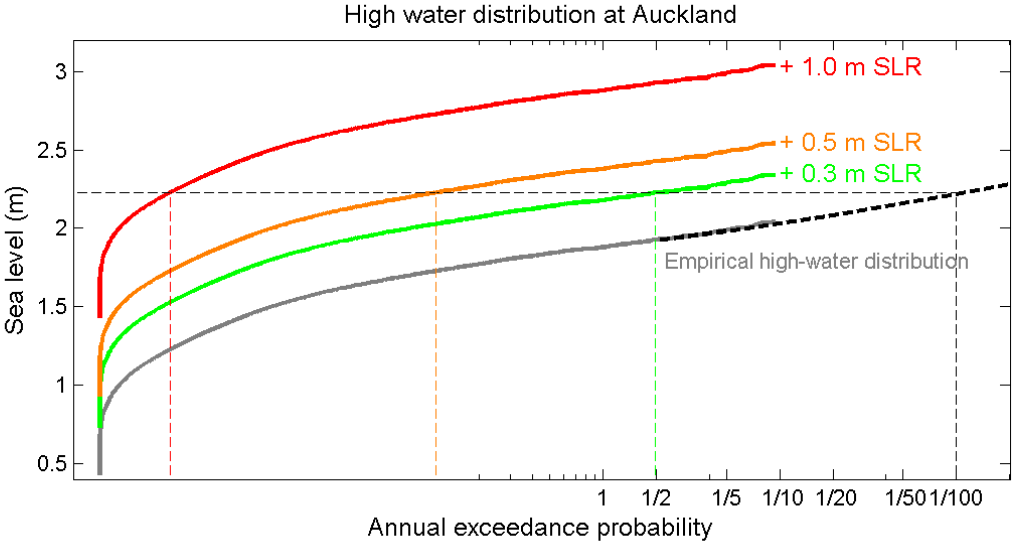

Figure 2-10: High-water distribution at Auckland plotted in terms of annual exceedance probability. Sea levels are specified relative to MSL = 0 (i.e., not relative to the local vertical datum). AEP ≈ 1/ARI for AEP ≤ 1/10. The empirical curves have been truncated at AEP = 1/10 (ARI = 10 years). The lower 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.

The horizontal axis in Figure 2-10 shows AEP. However, the exceedance probability can be can be reported using other measures, such as in Figure 2-11 which shows the expected number of exceedances in one year for the port at Auckland (using the conversions from AEP to *N* in Equation 2-1 and Equation 2-2). The present-day 0.01 AEP sea level is expected to have much less than 1 (0.01) exceedance every year at present-day MSL, about one exceedance on average every 2 years after a 0.3 m SLR, about 10 exceedances on average per year after a 0.5 m SLR, and several hundred exceedances per year after a 1.0 m SLR (Figure 2-11). Thus, what is now considered to be a large and infrequent sea level will be a frequent event in the future. For example, Figure 2-11 shows that the 23 January 2011 storm tide that inundated several parts of Auckland (the highest on record at Auckland, refer to Table A-1) has a present-day AEP of nearly 0.01. This sea-level measured during the 2011 event in Auckland is expected to be reached or exceeded:

- 0.5 times on average per year (once every 2 years) for a SLR of 0.3 m
- 10 times on average per year for a SLR of 0.5 m
- 292 times on average per year for a SLR of 1.0 m.

In addition to the increasing frequency of sea-levels reaching or exceeding high thresholds, Figure 2-10 and Figure 2-11 show that the total depth of large storm tides will also be raised as sea-level rises, so that inundation during future less-frequent extreme sea level events will be deeper and will reach further inland (compared to say the 2011 Auckland event).

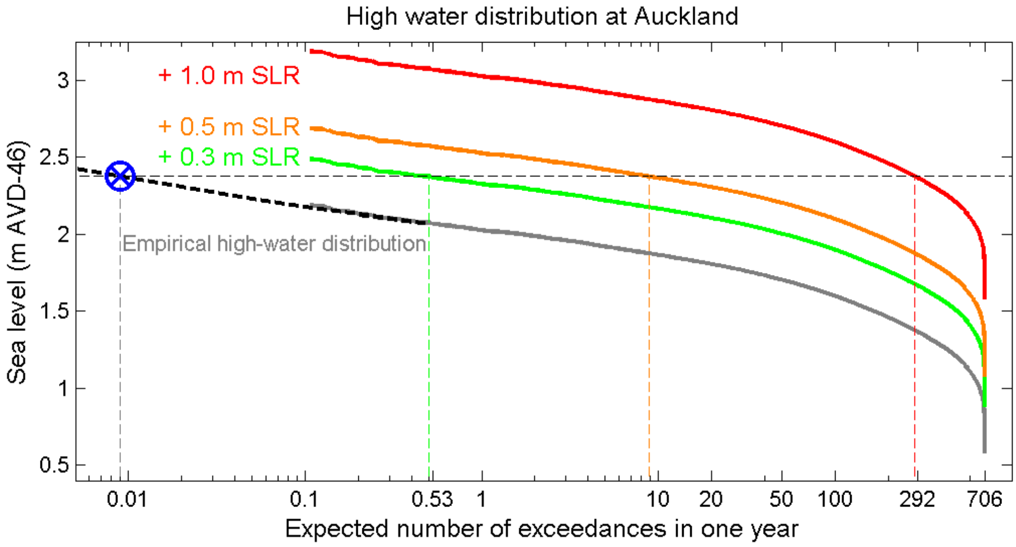

Figure 2-11: High-water distribution at Auckland plotted in terms of the expected number of exceedances in one year. ⊗ marks the position of the 23 January 2011 storm tide (the highest on record, see Table A-1) on the present-day extreme sea-level distribution curve. Sea levels are plotted relative to AVD–46. The empirical curves have been truncated at AEP = 0.1 (10-year ARI). 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 0.01 AEP extreme sea level. The vertical dashed lines show the expected change in the average number of exceedances in one year of the (present-day) 0.01 AEP sea level for SLR of 0.3, 0.5 and 1.0 m. There are 706 high tides per year, so high-tide exceedances are limited to this number.

3 Results

3.1 The effects of historical sea-level rise on sea-level exceedances

SLR over the last century has already increased the frequency of sea levels reaching high elevations, as illustrated in Figure 3-1 which shows the annual number of high waters exceeding the MHWPS, HAT and 1-year ARI elevations, relative to local vertical datum at the four sea-level gauge locations. At all sites the frequency of high sea levels increased during the measurement period. The increase in the frequency of exceedances is driven by historical relative SLR (Table 2-4).

In New Zealand, the MHWPS elevation is used to define the “red-alert” tide level. As explained by Stephens et al. (2014) the tide is the largest contributor to sea-level variability and to annual maximum sea-level elevation (relative to MSL) in New Zealand (Bell 2010), notwithstanding the effects of episodic extreme storms that occur less than once per year on average. An analysis of historical storm-tide events in New Zealand showed that extreme storm-tide levels around the open coast of New Zealand are usually dominated by very high spring tides coinciding with small to moderate storm surges, often compounded by high background SLA. This led to the development of a simple storm-tide “forecasting” approach, which is a pre-published list each year of red-alert days when high perigean-spring tides are predicted (see New Zealand Storm-Tide Red-Alert Days; NIWA web site[5]).

The “red-alert” concept works in New Zealand because the semi-diurnal tides dominate sea-level variability compared to storm surges which are limited to ≤ 1 m and mostly < 0.6 m i.e., only approximately 25% of the average tidal range (although a higher ratio in Wellington where there are smaller tides). Coastal or hazard managers are advised to keep a close watch on the weather for lower barometric pressure and adverse winds during the red-alert tide days, as even a minor storm could lead to inundation of low-lying areas, especially if accompanied by swell. For example, the highest storm-tide in Auckland (New Zealand) on record since 1903 occurred on 23 January 2011, closing major city highways, and causing a few million dollars of flood-related damage. At 0.4 m the storm surge height was high but not extreme, but it coincided with a predicted “red alert” tide, and a background SLA of nearly 0.1 m (25% of the storm-surge).

In the USA, (Sweet and Park 2014) observed an increase in *lesser extremes* such as occasional minor coastal flooding experienced during normal high tides. These events are becoming more noticeable and widespread along many U.S. coastal regions and increasingly more of a nuisance. Some places in New Zealand experience similar nuisance flooding during very high tides, with locations in Maraetai and Mission Bay (Auckland), south Dunedin and Nelson being examples (in Nelson very high tides occasionally enter carparks in the central business district through stormwater drains). Sweet et al. (2014) defined this “nuisance flooding” elevation on a site by site basis, being on average about 45 cm above MHWS. The 0.63 AEP (1-year ARI) elevation is 30–40 cm above MHWPS at the four locations considered here (Table 2-6), and is used to represent a “nuisance flooding” elevation for demonstration purposes, notwithstanding there may be local differences in what constitutes a nuisance inundation level.

Figure 3-1 shows the actual historical change in frequency of high waters that reached three sea-level thresholds. The historical sea-level exceedances are influenced by the interaction of all sea-level processes including climate variability, which affects SLA, and human modification of harbours

[5] https://www.niwa.co.nz/our-science/coasts/tools-and-resources/tide-resources

(reclamation and dredging). For example, the annual number of sea-level exceedances above the MHWPS elevation appears to be influenced by inter-decadal climate variability at Auckland (Figure 3-1), with several clusters of high sea-level exceedances over the last century.

To isolate the influence of historical SLR on sea-levels that exceed high thresholds, the method explained in Section 2.5 was applied to the empirical sea-level distributions, and the results are presented in Figure 3-2, Figure 3-3 and Table 3-1 to Table 3-4. The results (Figure 3-2 and Figure 3-3) show that Wellington is most sensitive to SLR of the four sites. Bell (2010) observed that locations with smaller tidal range (i.e., Wellington) would be more sensitive to SLR as they would experience a more rapid increase in the number of high waters that could overtop critical thresholds for inundation. The role of the tidal range in controlling sensitivity to SLR is discussed further in Section 3.3.

Historical SLR caused an approximately linear increase in the frequency of high waters reaching the MHWPS elevation (Figure 3-2), but there was a more rapid, approximately quadratic increase in the frequency of high waters reaching both the 1-year ARI elevations (Figure 3-3). Sweet et al. (2014) also observed a quadratic increase in “nuisance flooding” elevations in the United States. Nuisance flooding is more likely to be caused by the higher 1-year ARI elevation than the more commonly-experienced MHWPS elevation (with a cluster of high tides above this elevation peaking every 7 months when New or Full Moon coincides with the Moon in its perigee).

Figure 3-2 shows that the percentage of high waters reaching the MHWPS elevation increased by a factor of 3–4 from 1900–2010 at all sites. In other words there has been an approximate doubling in the number of red-alert *days* over the course of the last century, due to SLR.

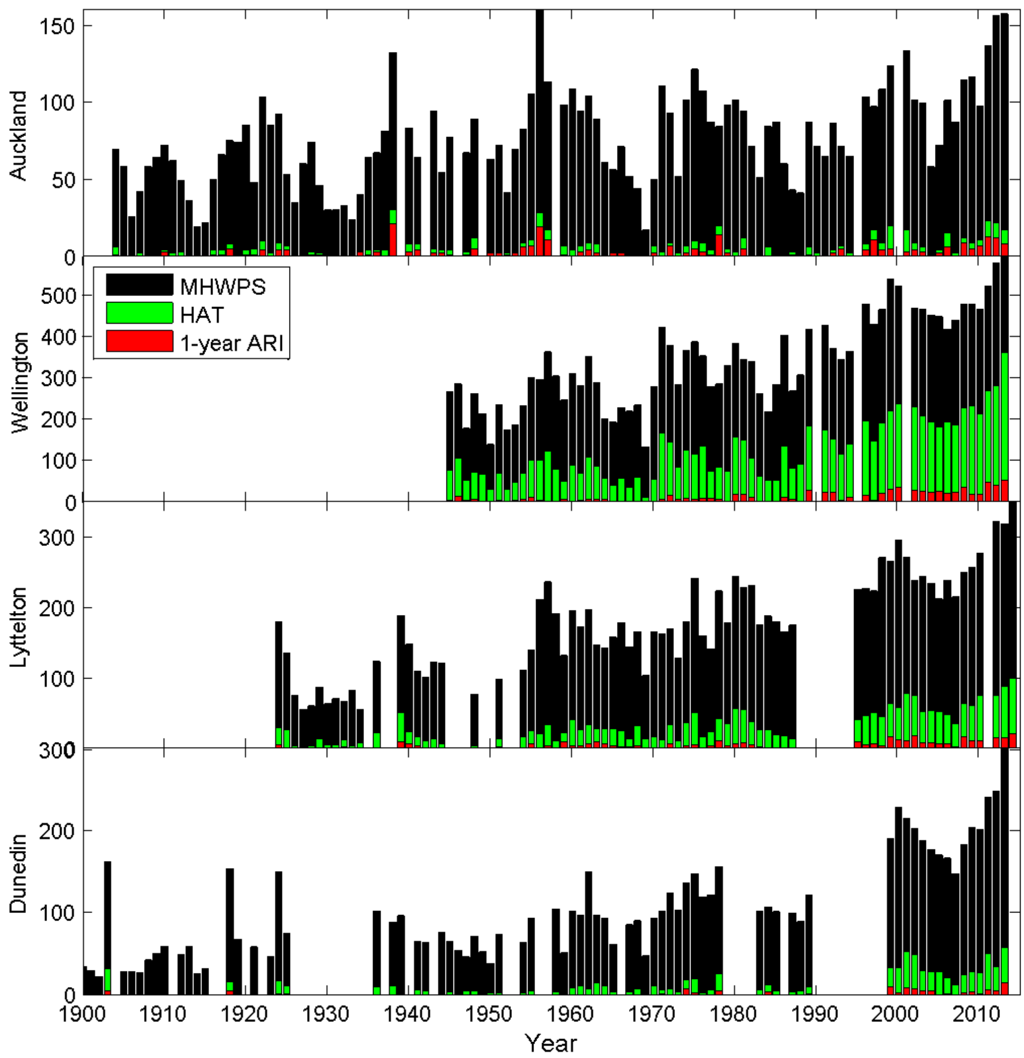

Figure 3-1: Annual number of high waters reaching MHWPS, HAT and 1-year ARI elevations relative to local vertical datum. The vertical axis marks the annual number of exceedances above the three threshold elevations: MHWPS = mean high-water perigean springs; HAT = highest astronomical tide. Only years with ≥ 80% of complete data are plotted. 1-year ARI = 63% AEP. Note that the vertical axis scale differs for each site.

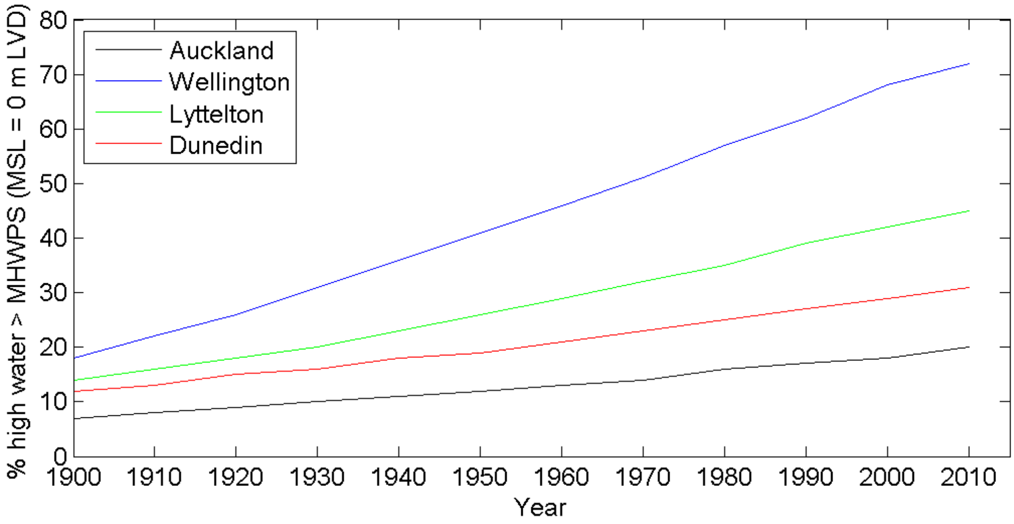

Figure 3-2: Theoretical change due to historical sea-level rise, in percent of high waters reaching MHWPS elevation. The MHWPS elevation includes a zero MSL offset to local vertical datum (LVD), which would have been the case for the period of data used to initially establish the LVD.

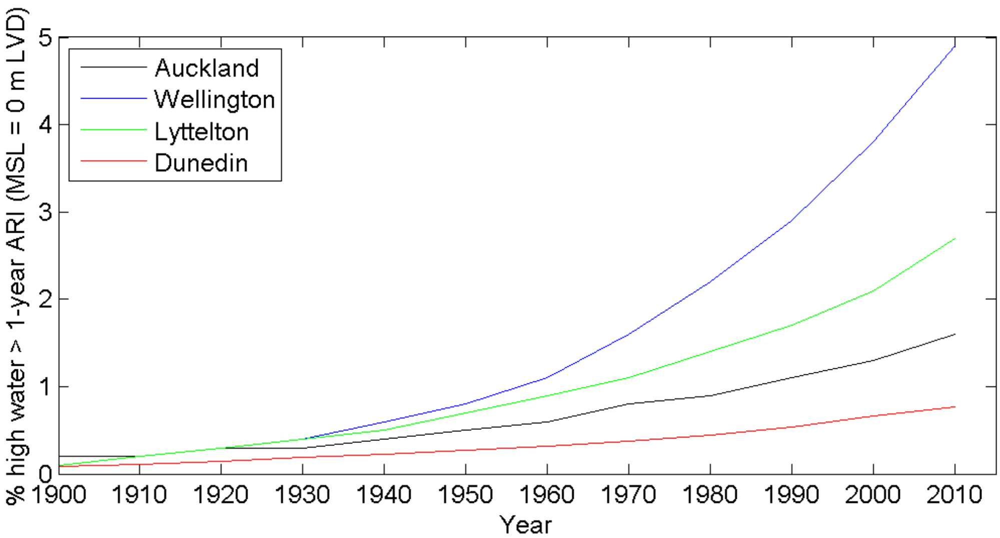

Figure 3-3: Theoretical change due to historical sea-level rise, in percent of high waters reaching 1-year ARI elevation. The 1-year ARI (63% AEP) elevation includes a zero MSL offset to local vertical datum (LVD) , which would have been the case for the period of data used to initially establish the LVD.

Table 3-1: Effect of 0.15 m per century historical sea-level rise on the percentage of high waters exceeding high sea-level thresholds at Auckland. Percentages are relative to MSL in the year 1900. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide.

Year	SLR (m)	Percent > MHWPS	Percent > HAT	Percent > 1-year ARI (63% AEP)	Percent > 10% AEP	Percent > 2% AEP	Percent > 1% AEP	Percent > 23 Jan 2011 storm tide	Percent > 2 Feb 2013 King Tide	Percent > 17 Apr 2014 Cyclone *Ita*
1900	0	7	0.4	0.2	0.02	0.004	0.002	0.002	0.1	0.2
1910	0.02	8	0.5	0.2	0.02	0.004	0.002	0.002	0.1	0.3
1920	0.03	9	0.6	0.3	0.03	0.005	0.003	0.003	0.1	0.3
1930	0.05	10	0.7	0.3	0.03	0.01	0.003	0.003	0.1	0.4
1940	0.06	11	0.9	0.4	0.04	0.01	0.004	0.003	0.2	0.5
1950	0.08	12	1.0	0.5	0.04	0.01	0.004	0.004	0.2	0.6
1960	0.09	13	1.2	0.6	0.1	0.01	0.005	0.004	0.3	0.8
1970	0.11	14	1.5	0.8	0.1	0.01	0.01	0.01	0.4	0.9
1980	0.12	16	1.8	0.9	0.1	0.01	0.01	0.01	0.5	1.1
1990	0.14	17	2.1	1.1	0.1	0.02	0.01	0.01	0.6	1.4
2000	0.15	18	2.5	1.3	0.1	0.02	0.01	0.01	0.7	1.7
2010	0.17	20	2.9	1.6	0.2	0.03	0.01	0.01	0.8	1.9

Table 3-2: Effect of 0.20 m per century historical sea-level rise on the percentage of high waters exceeding high sea-level thresholds at Wellington. Percentages are relative to MSL in the year 1900. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide.

Year	SLR (m)	Percent > MHWPS	Percent > HAT	Percent > 1-year ARI (63% AEP)	Percent > 10% AEP	Percent > 2% AEP	Percent > 1% AEP	Percent > 21 Jun 2013 storm tide	Percent > 7 Jun 2008 storm tide
1900	0	18	3	0.1	0.02	0.01		0.003	0.005
1910	0.02	22	5	0.2	0.02	0.01	0.01	0.01	0.01
1920	0.04	26	6	0.3	0.04	0.01	0.01	0.01	0.01
1930	0.06	31	8	0.4	0.07	0.02	0.01	0.01	0.01
1940	0.08	36	10	0.6	0.11	0.02	0.02	0.02	0.02
1950	0.10	41	12	0.8	0.19	0.04	0.02	0.03	0.03
1960	0.12	46	15	1.1	0.3	0.07	0.04	0.04	0.05
1970	0.14	51	18	1.6	0.4	0.12	0.07	0.08	0.10
1980	0.16	57	22	2.2	0.6	0.19	0.12	0.14	0.16
1990	0.18	62	26	2.9	0.8	0.26	0.19	0.22	0.23
2000	0.20	68	30	3.8	1.2	0.41	0.27	0.31	0.34
2010	0.22	72	35	4.9	1.7	0.60	0.41	0.46	0.53

Table 3-3: Effect of 0.19 m per century historical sea-level rise on the percentage of high waters exceeding high sea-level thresholds at Lyttelton. Percentages are relative to MSL in the year 1900. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide.

Year	SLR (m)	Percent > MHWPS	Percent > HAT	Percent > 1-year ARI (63% AEP)	Percent > 10% AEP	Percent > 2% AEP	Percent > 1% AEP	Percent > 17 Apr 1999 storm tide	Percent > 27 Jan 1940 storm tide	Percent > 17 May 2011 storm tide
1900	0	14	1.7	0.1	0.01	0.004	0.002	0.004		0.05
1910	0.02	16	2.1	0.2	0.02	0.007	0.004	0.007		0.09
1920	0.04	18	2.6	0.3	0.03	0.009	0.006	0.010	0.003	0.13
1930	0.06	20	3.2	0.4	0.05	0.01	0.009	0.013	0.005	0.2
1940	0.08	23	3.9	0.5	0.09	0.02	0.01	0.02	0.007	0.3
1950	0.10	26	4.7	0.7	0.13	0.03	0.02	0.03	0.011	0.4
1960	0.11	29	5.7	0.9	0.2	0.05	0.03	0.05	0.014	0.5
1970	0.13	32	6.9	1.1	0.3	0.08	0.04	0.08	0.02	0.7
1980	0.15	35	8.2	1.4	0.4	0.11	0.07	0.11	0.03	0.8
1990	0.17	39	9.7	1.7	0.5	0.18	0.11	0.18	0.05	1.1
2000	0.19	42	11.3	2.1	0.7	0.25	0.17	0.25	0.09	1.3
2010	0.21	45	13.1	2.7	0.8	0.34	0.25	0.34	0.13	1.7

Table 3-4: Effect of 0.13 m per century historical sea-level rise on the percentage of high waters exceeding high sea-level thresholds at Dunedin. Percentages are relative to MSL in the year 1900. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide.

Year	SLR (m)	Percent > MHWPS	Percent > HAT	Percent > 1-year ARI (63% AEP)	Percent > 10% AEP	Percent > 2% AEP	Percent > 1% AEP	Percent > 15 Jun 1999 storm tide	Percent > 23 Jul 2009 storm tide	Percent > 11 Jul 2011 storm tide
1900	0	12	0.9	0.09	0.004	0.002		0.002	0.059	0.25
1910	0.01	13	1.1	0.11	0.005	0.002	0.002	0.002	0.074	0.29
1920	0.03	15	1.3	0.15	0.009	0.003	0.002	0.003	0.098	0.35
1930	0.04	16	1.6	0.19	0.012	0.003	0.003	0.004	0.139	0.4
1940	0.05	18	1.9	0.22	0.02	0.004	0.003	0.00	0.172	0.5
1950	0.07	19	2.2	0.27	0.02	0.005	0.004	0.00	0.21	0.6
1960	0.08	21	2.6	0.32	0.03	0.006	0.004	0.01	0.26	0.7
1970	0.09	23	3.0	0.38	0.04	0.010	0.005	0.01	0.30	0.9
1980	0.10	25	3.4	0.44	0.05	0.013	0.009	0.01	0.36	1.0
1990	0.12	27	3.8	0.54	0.06	0.018	0.012	0.02	0.43	1.2
2000	0.13	29	4.3	0.66	0.08	0.024	0.017	0.03	0.51	1.4
2010	0.14	31	4.9	0.77	0.10	0.036	0.022	0.04	0.61	1.8

3.2 The effects of future sea-level rise on sea-level exceedances

The historically-observed SLR has been shown to cause increases in the frequency of extreme sea levels, even for relatively small SLR (Section 3.1). The rate of *future* SLR (i.e., the time frame to reach a particular SLR) is uncertain, but the recent IPCC AR5 report (Church et al. 2013a) provides four global SLR projection trajectories based on future greenhouse gas emissions scenarios (Figure 2-8). The highest (RCP8.5) and lowest (RCP2.6) of the SLR trajectories are used below to project the rate of increase in the frequency of extreme sea levels with time.

The analyses in Section 2.5 showed that future SLR will continue to increase the frequency of sea levels that are presently considered to be "extreme". The examples below focus on the 0.01 AEP sea-level elevation, which is often adopted as a design sea-level for coastal-hazard planning in New Zealand (Saunders 2010; Stephens and Bell 2015), being a high sea level that occurs infrequently when high tides and storm surges combine.[6]

The technique shown in Section 2.5 involves raising the (previously-measured) *high-water* distribution by a plausible future SLR to determine how SLR will increase the frequency of sea levels that are presently considered to be "extreme". The distribution of high-water peaks is useful to examine the exposure to inundation because it includes coincident combinations of tide, SLA and storm surge, some of which will result in large and relatively infrequent "extreme" sea levels, but most of which represent "normal" sea levels at high tide. A key assumption of the technique is that the future high-water distribution will remain the same as previously measured, but raised upward due to SLR. In fact, we don't know exactly what storm-tide levels will occur in future, nor how the high-water distribution will change. However, it is reasonable to assume that the high-water distribution will remain similar to present for more-frequent (smaller) high waters, which result from less-extreme combinations of SLA, high tide and storm surge. Figure 2-10 shows that SLR will shift the occurrence of present-day "extreme" sea levels towards the more frequent end of the high-water distribution.

Data have been analysed and plotted from all four sites, however the explanations in the text focus on the sea-level records from Auckland and Wellington, because these represent the highest and lowest sea levels, and are the least and most sensitive to SLR, respectively. The Lyttelton and Dunedin sea-level records plot between the Auckland and Wellington records.

The expected increase in frequency, due to SLR, of high waters reaching the present-day 0.01 AEP storm-tide elevation has been plotted in terms of:

1. the percentage of high-waters reaching or exceeding that level (Figure 3-4)
2. the change in AEP with time (Figure 3-5), and
3. the expected number of high-waters per year reaching or exceeding that level (Figure 3-6).

[6] Note: for the minimum planning horizon of at least 100 years required in the NZ Coastal Policy Statement, an event with a 0.01 (1%) AEP would have a 63% chance of occurrence in that timeframe.

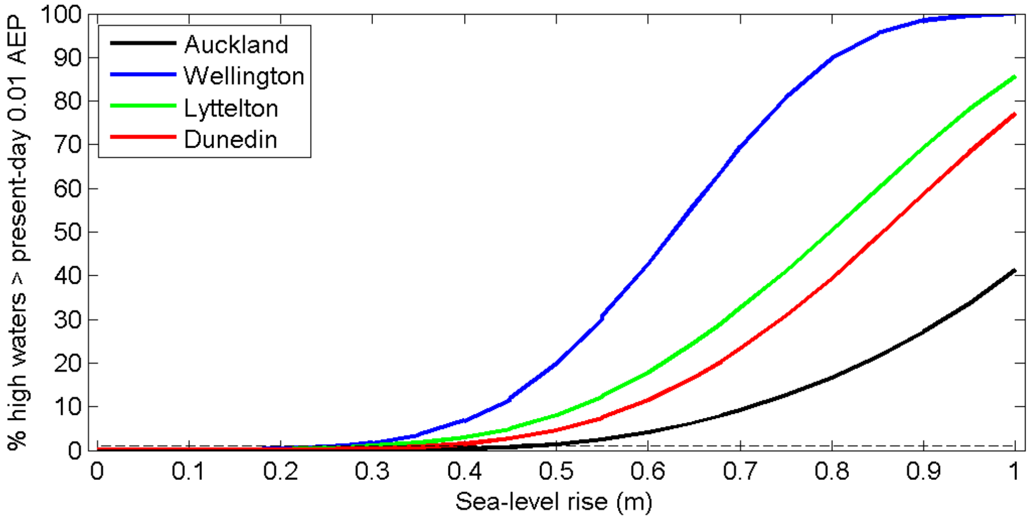

Figure 3-4: Change, due to sea-level rise, in the percent of high waters reaching or exceeding the present-day 0.01 AEP storm-tide elevation.

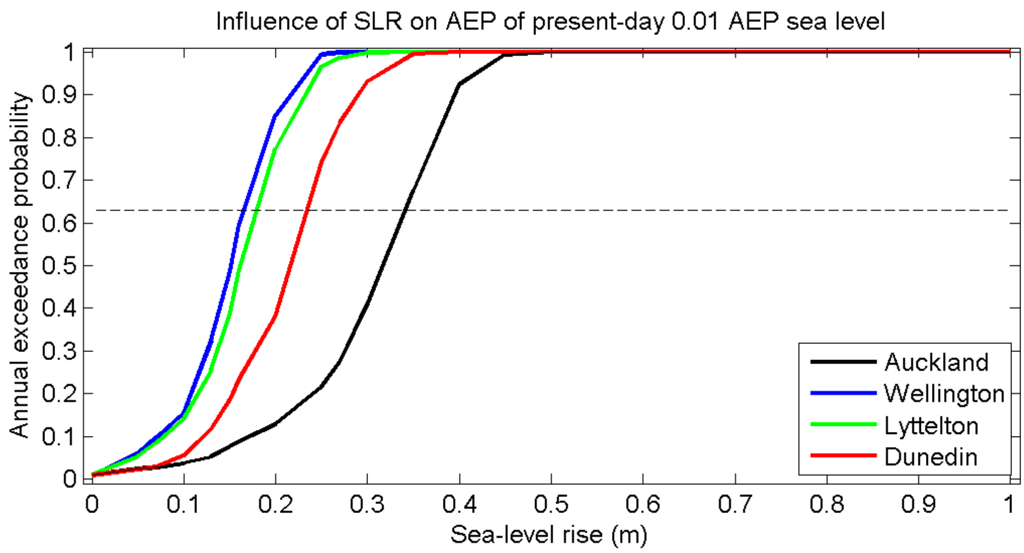

Figure 3-5: Change, due to sea-level rise, in the annual exceedance probability of sea-levels reaching the present-day 0.01 AEP storm-tide elevation. The 0.63 AEP (equivalent to a 1-year ARI) has been marked (horizontal dashed line), showing that a 0.01 AEP sea-level at present-day MSL is expected to be reached or exceeded at least once per year (on average), at all sites, after SLR of 0.33 m.

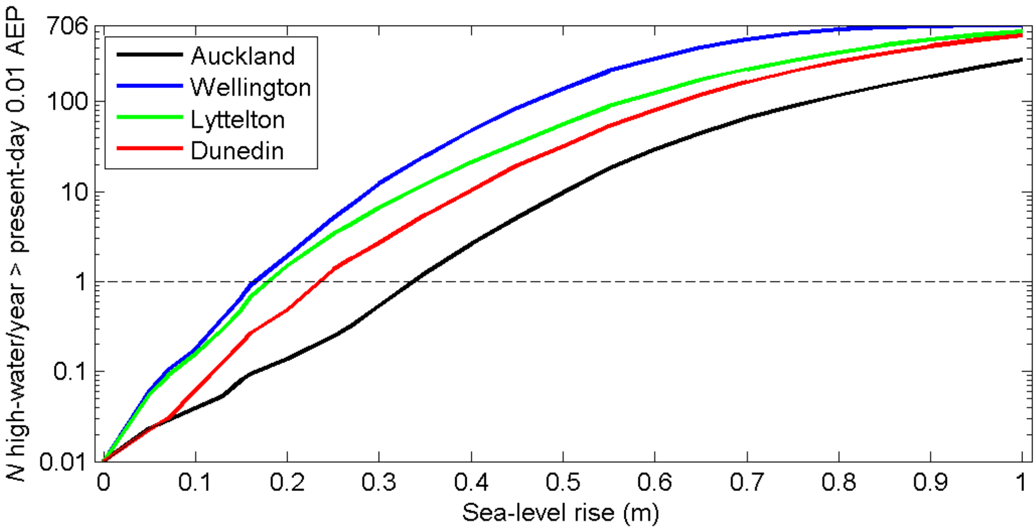

Figure 3-6: Change, due to sea-level rise, in the number of high-waters per year that reach or exceed the present-day 0.01 AEP storm-tide elevation. There are 706 high tides per year.

Figure 3-4 shows that:

- Large increases in the percentage of high waters reaching or exceeding extreme sea-level elevations will occur after a SLR of only 0.3–0.5 m.
- Sites with small tidal range, such as Wellington (Table 2-6), will experience a greater increase in the number of high waters reaching or exceeding present-day extreme sea levels than sites with a larger tidal range such as Auckland.
- After a 1 m SLR, the percentage of high waters reaching or exceeding present-day extreme sea levels will be high, occurring at least fortnightly on spring tides at all four port sites, and exceeded by every (100%) high tide for sites with small tidal range such as Wellington. Note that a 1 m SLR is considered appropriate for coastal hazard planning purposes over a 100-year timeframe to 2115, (Britton et al. 2011; MfE 2008; Stephens and Bell 2015).

Figure 3-5 presents the change in AEP of the present-day 0.01 AEP sea-level elevation, and shows that:

- Present-day extreme sea levels are expected to be reached at least once every year (AEP = 0.63) after only 0.16–0.33 m SLR.
- AEP is most sensitive to SLR (decreases fastest) at locations with small tidal range such as Wellington (0.16 m SLR to reach AEP = 0.63), and is least sensitive at locations with large tidal range such as Auckland (0.33 m SLR to reach AEP = 0.63).

Figure 3-6 presents the expected number of high-waters per year reaching the present-day 0.01 AEP sea-level elevation, and shows that:

- Present-day extreme sea levels are expected to be reached at least once every year after only 0.16–0.33 m SLR.

- The number of exceedances per year is most sensitive to SLR (increases fastest) at locations with small tidal range such as Wellington (only 0.16 m SLR to reach 1 exceedance per year of the present-day 0.01 AEP event), and is least sensitive at locations with a larger tidal range such as Auckland (0.33 m SLR to reach 1 exceedance per year).
- In other words, extreme sea-levels that are expected to be reached only once every 100 years (on average) at present-day MSL, will occur at least once per year or more (on average), at <u>all</u> four port sites, after a 0.33 m SLR.
- Present-day extreme sea levels are expected to be reached about *ten times every year* after 0.28 m SLR in Wellington up to a 0.50 m SLR in Auckland, with Lyttelton and Dunedin within this SLR range.
- Present-day extreme sea levels are expected to be reached on spring tides *every fortnight* after a 0.35 m SLR in Wellington up to a 0.59 m SLR in Auckland, with Lyttelton and Dunedin within this SLR range.
- There will be hundreds of occurrences per year of extreme sea levels exceeding the present-day infrequent 0.01 AEP event, at all sites, if SLR reaches 1 m, with every high tide in Wellington exceeding this present-day level.

The highest (RCP8.5) and lowest (RCP2.6) of the SLR trajectories are used below to project the rate of increase in the frequency of extreme sea levels with time. Figure 3-7 shows, for example, how the number of high waters reaching the present-day MHWPS is projected to change if SLR follows either the highest RCP8.5, or the lowest RCP2.6 median trajectories published in the IPCC AR5. Figure 3-7 looks similar to Figure 3-4, except that SLR has now been linked to the rate of rise along the horizontal axis. Wellington is most sensitive to SLR due to its relatively small tidal range, while Auckland is conversely the least sensitive. At all locations, 100% of high waters are expected to exceed the present-day MHWPS elevation at each site by 2120 following the RCP8.5 SLR median trajectory. Figure 3-7 also shows that irrespective of whether SLR follows a low or high trajectory (comparing the same-colour bold or dashed lines), the same % exceedance of high waters is reached within a 30 year window for Wellington and 36–40 years for the other port sites. This result clearly illustrates that planning for SLR is a matter of being adaptable within relatively short windows of variability, rather than focusing too much on the magnitude of SLR in isolation.

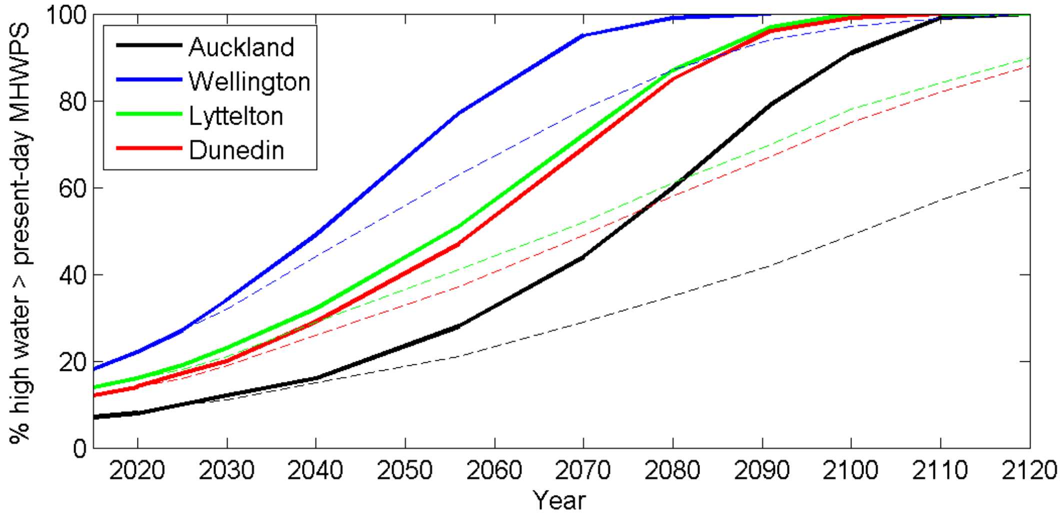

Figure 3-7: Projected change in percent of high waters reaching or exceeding MHWPS due to projected SLR. Bold lines indicate the IPCC AR5 RCP8.5 median trajectory, and dashed lines mark the RCP2.6 median trajectory. MHWPS elevations are specified relative to present-day (2015) MSL.

Figure 3-8 shows that the 0.01 AEP sea-level elevation is seldom reached or exceeded at present-day MSL (1% chance per year), but projected SLR will noticeably increase the frequency of sea-levels reaching these elevations by 2045 (vertical dashed line). Regardless of the pathway followed, by 2045, about the lifetime of an average 30-year mortgage from now, the annual chance of such a high sea level being reached or exceeded in a year will have increased from 1%, to 6% at Auckland, and to 52% chance at Wellington.

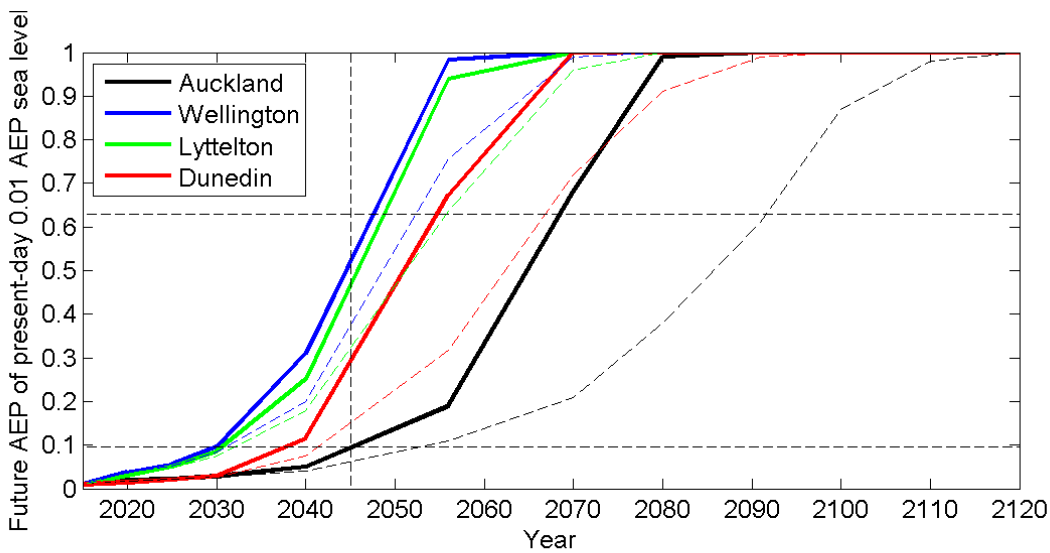

Figure 3-8: Projected change in AEP due to projected SLR, of present-day 1% AEP sea level. Bold lines indicate the IPCC AR5 RCP8.5 median trajectory, and dashed lines mark the RCP2.6 median trajectory.

To create Figure 3-9, the information in Figure 3-8 was transformed using Equation 2-4 to plot the expected average number of exceedances in one year. Figure 3-9 shows that (with the exception of Auckland for the RCP2.6 trajectory) by 2048–2068 there will be around one event or more per year that reaches or exceeds the present 0.01 AEP “extreme” sea level, and that this will occur for both the fastest *and slowest* SLR rate trajectories. However, for sites with large tidal range such as Auckland, this might be delayed by 1–2 decades if SLR proceeds more slowly than anticipated. Note that Figure 3-9 has a logarithmic vertical axis, so once this annual occurrence threshold is reached, the number of sea levels exceeding this threshold will increase rapidly in time.

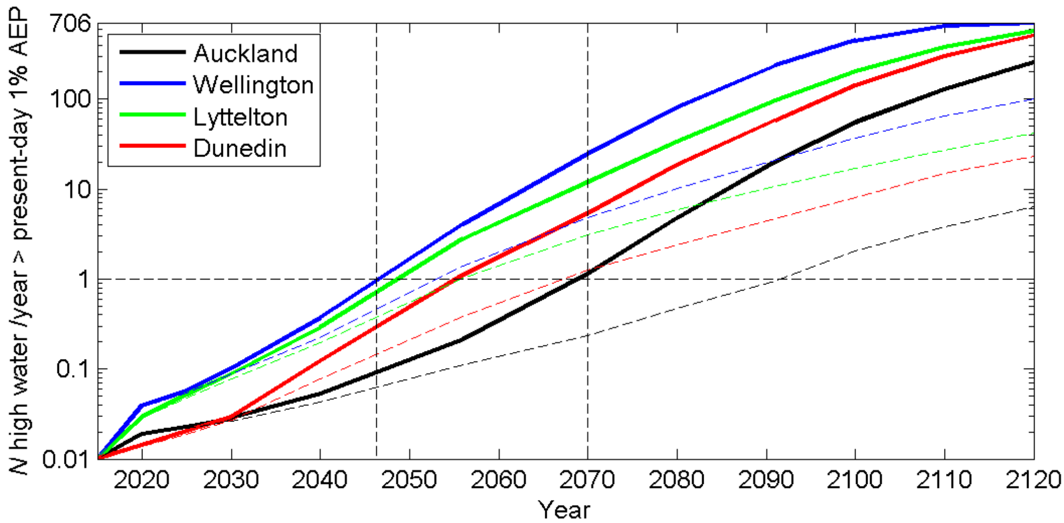

Figure 3-9: Projected change in average annual number *N* of high waters *per year* reaching or exceeding the present-day 0.01 AEP elevation. Solid lines represent the median IPCC AR5 RCP8.5 SLR trajectory and dashed lines represent RCP2.6 median trajectory.

Figure 3-10 shows that “nuisance flooding” events that occur about once per year (0.63 AEP) at present-day MSL will occur about 10-times per year by about 2045.

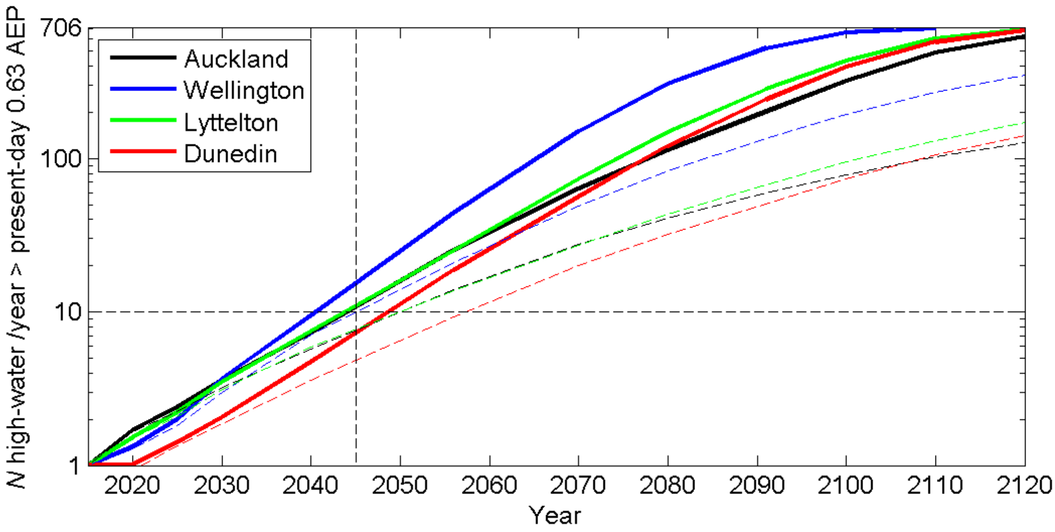

Figure 3-10: Projected change in average annual number *N* of high waters per year reaching or exceeding the present-day 0.63 AEP elevation (1-year ARI). Solid lines represent the median IPCC AR5 RCP8.5 SLR trajectory and dashed lines represent RCP2.6 median trajectory. These "nuisance flooding" events that occur about once per year at present-day MSL will occur about 10-times per year by about 2045.

Based on the four sea-level records, Table 3-5 to Table 3-8 show the percentage of high waters that exceed several sea-level elevations (defined in Table A-1) at present-day (2015) MSL, and the expected change in those exceedance percentages for each of the four IPCC AR5 SLR trajectories (Figure 2-8). For example, approximately 7% of all high-waters equal or exceed the MHWPS elevation at present-day MSL at Auckland (Table 3-5). If SLR follows the RCP2.6 trajectory then we expect 49% of all high-waters to equal or exceed the MHWPS elevation by the year 2100. If SLR follows the RCP8.5 trajectory then we expect 91% of all high-waters to exceed MHWPS by 2100 (Table 3-5).

Table 3-5: Future sea-level rise effects on the percentage of high waters exceeding high sea-level thresholds at Auckland. Percentages are relative to present-day (2015) MSL; and are shown for the four IPCC AR5 SLR projections (RCP), Figure 2-8. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide. Percentages are rounded to the nearest integer, thus values <0.5 are shown as 0.

	Percent > MHWPS				Percent > HAT				Percent > 63% AEP (1-year ARI)			
Year	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	7	7	7	7	0.4	0.4	0.4	0.4	0.14	0.14	0.14	0.14
2020	8	8	8	8	1	1	1	1	0.2	0.2	0.2	0.2
2025	10	10	10	10	1	1	1	1	0.3	0.3	0.3	0.3
2030	11	11	11	12	1	1	1	1	0.5	0.4	0.5	0.5
2040	15	15	15	16	2	2	2	2	1	1	1	1
2056	21	23	22	28	4	4	4	6	2	2	2	4
2070	29	33	32	44	6	8	7	13	4	5	5	9
2080	35	43	42	60	9	12	12	21	6	9	8	16
2091	42	54	54	79	12	18	18	36	8	13	14	29
2100	49	63	66	91	15	23	25	54	11	18	19	45
2110	57	74	77	99	19	32	34	77	15	25	27	69
2120	64	84	87	100	24	43	47	94	18	34	38	89
	Percent > 10% AEP				**Percent > 2% AEP**				**Percent > 1% AEP**			
Year	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
2015	0.015	0.015	0.015	0.015	0.003	0.003	0.003	0.003	0.001	0.001	0.001	0.001
2020	0.02	0.02	0.02	0.02	0.004	0.004	0.004	0.004	0.003	0.003	0.003	0.003
2025	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.01	0.003	0.003	0.003	0.003
2030	0.04	0.04	0.04	0.04	0.01	0.01	0.01	0.01	0.004	0.004	0.004	0.004
2040	0.08	0.08	0.08	0.11	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
2056	0.26	0.34	0.29	0.57	0.03	0.04	0.03	0.07	0.02	0.02	0.02	0.03
2070	1	1	1	2	0.08	0.14	0.12	0.44	0.03	0.06	0.05	0.16
2080	1	2	2	6	0.17	0.40	0.34	1.48	0.07	0.15	0.13	0.68
2091	2	4	4	13	0.36	0.97	0.98	5.11	0.14	0.45	0.46	2.85
2100	3	7	7	24	1	2	2	12	0	1	1	8
2110	5	11	12	43	1	4	5	24	1	2	3	18
2120	7	17	19	68	2	7	9	46	1	4	6	36
	Percent > 23-Jan-2011 storm tide				**Percent > 17 Apr 2014 cyclone *Ita***				**Percent > 2 Feb 2013 King Tide**			
Year	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
2015	0.002	0.002	0.002	0.002	0.07	0.07	0.07	0.07	0.1	0.1	0.1	0.1
2020	0.002	0.002	0.002	0.002	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1
2025	0.003	0.003	0.003	0.003	0.4	0.4	0.4	0.4	0.1	0.1	0.1	0.1
2030	0.004	0.003	0.004	0.004	0.6	0.6	0.6	0.6	0.2	0.2	0.2	0.2
2040	0.01	0.01	0.01	0.01	1.0	1.0	1.0	1.3	0.4	0.4	0.4	0.5
2056	0.01	0.02	0.02	0.03	2	3	3	4	1.0	1.3	1.1	2
2070	0.03	0.05	0.04	0.15	5	6	6	10	2	3	3	6
2080	0.06	0.13	0.12	0.62	7	10	9	18	4	6	5	12
2091	0.13	0.41	0.42	2.64	9	15	15	31	6	10	10	22
2100	0.3	0.8	1.0	7	12	19	21	48	8	13	15	37
2110	1	2	2	18	16	27	29	72	11	19	21	60
2120	1	4	5	35	20	37	41	90	14	27	31	83

Table 3-6: Future sea-level rise effects on the percentage of high waters exceeding high sea-level thresholds at Wellington. Percentages are relative to present-day (2015) MSL; and are shown for the four IPCC AR5 SLR projections (RCP), Figure 2-8. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide. Percentages are rounded to the nearest integer, thus values <0.5 are shown as 0.

Year	Percent > MHWPS				Percent > HAT				Percent > 63% AEP (1-year ARI)			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	18	18	18	18	3	3	3	3	0.14	0.14	0.14	0.14
2020	22	22	22	22	5	5	5	5	0.18	0.18	0.18	0.19
2025	27	26	27	27	6	6	6	6	0.26	0.26	0.26	0.28
2030	32	32	32	34	8	8	8	9	0.42	0.41	0.44	0.52
2040	44	44	45	49	14	14	14	17	1.0	1.0	1.1	1.4
2056	63	68	65	77	26	31	28	40	3	4	3	6
2070	78	85	83	95	42	51	48	70	7	11	9	21
2080	87	94	93	99	54	68	66	89	12	20	18	43
2091	94	99	99	100	67	83	84	99	19	35	35	74
2100	97	100	100		77	92	94	100	28	48	52	94
2110	99	100	100		86	98	99		38	67	72	100
2120	100	100			92	100	100		49	84	88	

Year	Percent > 10% AEP				Percent > 2% AEP				Percent > 1% AEP			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	0.014	0.014	0.014	0.014	0.003	0.003	0.003	0.003	0.001	0.001	0.001	0.001
2020	0.023	0.023	0.023	0.024	0.007	0.007	0.007	0.008	0.005	0.005	0.005	0.006
2025	0.04	0.04	0.04	0.04	0.011	0.011	0.012	0.013	0.008	0.008	0.008	0.008
2030	0.07	0.07	0.08	0.10	0.017	0.017	0.019	0.022	0.012	0.012	0.013	0.014
2040	0.23	0.23	0.24	0.33	0.053	0.056	0.062	0.095	0.032	0.032	0.033	0.053
2056	0.87	1.20	0.98	2.1	0.28	0.43	0.32	0.83	0.20	0.28	0.23	0.58
2070	2.4	3.9	3.3	9.4	1.0	1.7	1.4	4.5	0.7	1.2	1.0	3.5
2080	4	9	8	24	2	4	4	14	1	3	3	11
2091	8	18	18	54	4	10	10	38	3	8	8	33
2100	13	28	32	82	7	17	19	69	5	14	16	64
2110	21	46	51	98	11	31	35	94	9	26	31	92
2120	29	65	72	100	17	50	57	100	14	45	52	100

Year	Percent > 21 Jun 2013 storm tide				Percent > 7 Jun 2008 storm tide			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	0.003	0.003	0.003	0.003	0.005	0.005	0.005	0.005
2020	0.006	0.006	0.006	0.006	0.007	0.007	0.007	0.007
2025	0.008	0.008	0.008	0.009	0.009	0.009	0.009	0.010
2030	0.014	0.013	0.014	0.015	0.015	0.015	0.015	0.017
2040	0.03	0.04	0.04	0.07	0.04	0.04	0.04	0.07
2056	0.23	0.32	0.25	0.65	0.24	0.36	0.26	0.70
2070	0.7	1.3	1.1	3.7	0.8	1.5	1.2	4
2080	2	3	3	12	2	4	3	13
2091	3	8	8	35	3	9	9	36
2100	6	14	17	65	6	15	18	66
2110	10	28	32	93	10	29	33	93
2120	15	46	53	100	16	47	54	100

Table 3-7: Future sea-level rise effects on the percentage of high waters exceeding high sea-level thresholds at Lyttelton. Percentages are relative to present-day (2015) MSL; and are shown for the four IPCC AR5 SLR projections (RCP), Figure 2-8. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide. Percentages are rounded to the nearest integer, thus values <0.5 are shown as 0.

Year	Percent > MHWPS				Percent > HAT				Percent > 63% AEP (1-year ARI)			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	14	14	14	14	1.7	1.7	1.7	1.7	0.14	0.14	0.14	0.14
2020	16	16	16	16	2.1	2.1	2.1	2.1	0.21	0.21	0.21	0.22
2025	18	18	18	19	2.8	2.8	2.8	2.9	0.29	0.29	0.30	0.31
2030	21	21	22	23	3.5	3.4	3.5	3.8	0.44	0.44	0.45	0.49
2040	29	29	29	32	5.6	5.6	5.8	6.8	0.84	0.84	0.87	1.06
2056	41	44	42	51	11	12	11	16	1.9	2.4	2.1	3.6
2070	52	59	57	72	17	22	20	33	3.8	5.6	4.9	10.4
2080	61	71	69	87	23	32	30	50	6	10	9	21
2091	70	82	83	97	31	43	44	72	10	17	17	40
2100	78	89	91	100	38	53	56	89	13	24	26	61
2110	84	95	97	100	46	66	70	98	19	35	38	85
2120	90	99	99	100	54	79	83	100	24	48	53	98

Year	Percent > 10% AEP				Percent > 2% AEP				Percent > 1% AEP			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2020	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
2025	0.03	0.03	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2030	0.06	0.06	0.07	0.08	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
2040	0.19	0.19	0.20	0.26	0.04	0.04	0.05	0.07	0.03	0.03	0.03	0.04
2056	0.58	0.76	0.66	1.19	0.22	0.30	0.25	0.54	0.14	0.22	0.17	0.40
2070	1.3	2.0	1.7	4	0.6	1.0	0.8	2.1	0.4	0.7	0.6	1.7
2080	2	4	4	10	1.1	2.0	1.9	5.8	0.8	1.6	1.4	4.7
2091	4	8	8	24	2	4	4	16	2	3	3	14
2100	6	12	13	43	3	7	8	32	2	6	7	29
2110	9	20	22	69	5	13	15	58	4	11	12	54
2120	12	31	35	92	7	21	25	84	6	19	22	81

Year	Percent > 17 Apr 1999 storm tide				Percent > 27 Jan 1940 storm tide				Percent > 17 May 2011 storm tide			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	0.00	0.00	0.00	0.00					0.05	0.05	0.05	0.05
2020	0.01	0.01	0.01	0.01		0.00	0.00	0.00	0.09	0.09	0.09	0.09
2025	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.14	0.14	0.14	0.16
2030	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.23	0.22	0.23	0.25
2040	0.04	0.04	0.05	0.07	0.01	0.01	0.01	0.02	0.49	0.49	0.50	0.64
2056	0.23	0.30	0.25	0.54	0.07	0.11	0.08	0.24	1.22	1.56	1.32	2.29
2070	0.59	0.97	0.82	2.14	0.26	0.48	0.40	1.17	2.5	3.7	3.3	7.4
2080	1.1	2.0	1.9	6	0.5	1.1	1.0	3	4	7	6	16
2091	1.9	4.2	4.3	16	1.0	2.4	2.4	11	7	12	13	33
2100	3	7	8	32	2	4	5	24	10	18	20	54
2110	5	13	15	58	3	8	10	48	14	28	31	79
2120	7	21	25	84	4	15	18	76	19	41	45	96

Table 3-8: Future sea-level rise effects on the percentage of high waters exceeding high sea-level thresholds at Dunedin. Percentages are relative to present-day (2015) MSL; and are shown for the four IPCC AR5 SLR projections (RCP), Figure 2-8. MHWPS = mean high-water perigean springs; HAT = highest astronomic tide. Percentages are rounded to the nearest integer, thus values <0.5 are shown as 0.

	Percent > MHWPS				Percent > HAT				Percent > 63% AEP (1-year ARI)			
Year	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	12	12	12	12	0.9	0.9	0.9	0.9	0.14	0.14	0.14	0.14
2020	14	14	14	14	1.2	1.2	1.2	1.2	0.13	0.13	0.13	0.14
2025	16	16	16	17	1.7	1.7	1.7	1.8	0.19	0.19	0.19	0.20
2030	19	19	19	20	2.2	2.2	2.3	2.5	0.26	0.26	0.27	0.29
2040	26	26	26	29	4	4	4	4	0.51	0.51	0.53	0.67
2056	37	41	38	47	7	9	8	12	1.3	1.8	1.4	3
2070	49	56	54	69	13	16	15	26	2.8	4.1	3.6	8
2080	58	68	67	85	18	25	24	41	5	7	7	17
2091	67	80	80	96	24	35	36	65	7	14	14	34
2100	75	87	89	99	30	45	48	84	10	19	22	56
2110	82	94	95	100	38	59	62	97	15	30	32	81
2120	88	98	99		46	72	77	100	20	42	47	96

	Percent > 10% AEP				Percent > 2% AEP				Percent > 1% AEP			
Year	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	0.014	0.014	0.014	0.014	0.003	0.003	0.003	0.003	0.001	0.001	0.001	0.001
2020	0.007	0.007	0.007	0.007	0.002	0.002	0.002	0.003	0.002	0.002	0.002	0.002
2025	0.012	0.012	0.012	0.013	0.004	0.004	0.004	0.004	0.003	0.003	0.003	0.003
2030	0.022	0.022	0.022	0.029	0.005	0.004	0.005	0.005	0.004	0.004	0.004	0.004
2040	0.057	0.057	0.060	0.086	0.016	0.016	0.017	0.025	0.011	0.011	0.012	0.017
2056	0.22	0.29	0.24	0.45	0.06	0.10	0.07	0.20	0.05	0.07	0.06	0.16
2070	0.51	0.86	0.73	2.16	0.22	0.37	0.31	0.92	0.18	0.29	0.26	0.77
2080	1.0	2.0	1.8	5.6	0.4	0.9	0.8	3.1	0.3	0.7	0.6	2.6
2091	1.9	4	4	16	0.8	2.2	2.2	10	0.7	1.8	1.8	8
2100	3.0	7	8	31	1.4	3.7	4.3	22	1.1	3.1	3.7	20
2110	5	12	14	58	2.6	7	9	46	2.1	6.3	7.4	43
2120	7	21	25	84	4	14	17	74	3	12	15	72

	Percent > 15 Jun 1999 storm tide				Percent > 23 Jul 2009 storm tide				Percent > 11 Jul 2011 storm tide			
Year	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2015	0.002	0.002	0.002	0.002	0.06	0.06	0.06	0.06	0.25	0.25	0.25	0.25
2020	0.003	0.003	0.003	0.003	0.09	0.09	0.09	0.09	0.33	0.33	0.33	0.33
2025	0.004	0.004	0.004	0.004	0.14	0.14	0.14	0.15	0.43	0.43	0.44	0.45
2030	0.005	0.005	0.005	0.006	0.21	0.20	0.21	0.23	0.60	0.60	0.62	0.68
2040	0.019	0.019	0.020	0.030	0.39	0.40	0.41	0.51	1.11	1.13	1.17	1.45
2056	0.07	0.11	0.09	0.22	1.0	1.4	1.1	2.2	2.8	3.4	3.0	5
2070	0.25	0.40	0.33	1.00	2.4	3.5	3.1	6.8	5.2	7.3	6.5	13
2080	0.45	0.92	0.85	3.33	3.8	6.4	5.9	15.2	8	13	12	25
2091	0.9	2.3	2.4	10	6	12	12	32	12	21	21	45
2100	1.5	3.9	4.6	23	9	17	19	53	17	28	30	68
2110	3	8	9	47	13	27	30	79	23	40	43	89
2120	4	14	17	75	18	39	44	95	29	54	59	99

3.3 Tidal controls on sensitivity to sea-level rise

The calculations show that locations with smaller tidal range are more sensitive to SLR, as they experience a more rapid increase in the frequency of high water peaks reaching extreme sea levels.

The reason for this is that the tide constitutes most of the sea-level variability in New Zealand (even at the sites with smaller tides, like Wellington). Thus, extreme sea-levels always peak at or close to high tide (unless driven by very large wave events – which are not considered in this report as the sea-level gauges are located in wave-sheltered locations), and consequently the tide will always make up a large fraction of the total sea level.

Where tides are small, SLR forms a greater proportion of the tide compared with other areas with higher tide ranges, and therefore a greater proportion of the total sea-level height.

Furthermore, locations with small high-tide ranges have “flatter” sea-level distributions – there is less sea-level range between a more frequent (e.g., 0.63 AEP) and infrequent (e.g., 0.01 AEP) sea level event.

For example, Figure 3-11 shows that:

- The predicted tide-only high-water distributions form the main base for the high-water distributions for more frequent occurrences – the distributions merge at lower water levels at the high-frequency ends (left hand side). The distributions depart at higher extreme sea levels at the low-frequency ends (right hand side), because non-tidal contributions (e.g., storm surge) form an increasingly-large component of the highest and least-frequent sea levels.
- High tide and high water are higher at Auckland than at Wellington, and the difference between them is mainly governed by the tide.
- The vertical range of both the high-tide and the high-water distributions are larger at Auckland than at Wellington.
- The slope of both the high-tide and the high-water distributions are flatter at Wellington than at Auckland.
- The flatter distribution means that SLR causes a greater increase in the frequency of high sea levels relative to present-day MSL – this is illustrated by the change in frequency of highest astronomical tide (HAT) that presently occurs approximately every 19 years when the nodal tide peaks. Comparing Wellington with Auckland, the HAT will be exceeded 285 times a year compared with 50 times for Auckland, after 0.3 m SLR.
- At either site the present-day 0.01 AEP storm tide elevation will be similar to HAT (no weather effects) following a 0.3 m SLR, although Wellington is more sensitive to SLR for the aforementioned reasons.

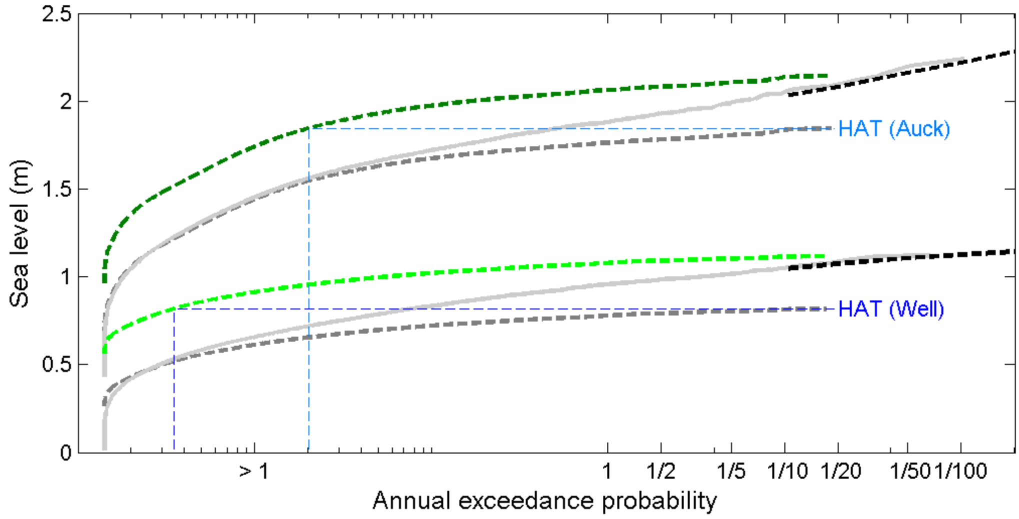

Figure 3-11: Comparison of empirical high-water and predicted-high-tide-only sea-level distributions at Auckland and Wellington, including 0.3 m SLR. Grey dashed lines = predicted tide-only high water, light-grey solid lines = empirical (measured) high water, dashed black lines = extreme sea-level distribution, green dashed lines = predicted tide-only high water distribution + 0.3 m SLR. The lower curves correspond to Wellington, the upper curves to Auckland. Sea levels are specified relative to MSL = 0 (i.e., not relative to a fixed datum). AEP ≈ 1/ARI for AEP ≤ 1/10.

4 Conclusions

In 2014, the Parliamentary Commissioner for the Environment (PCE) published the report “Changing climate and rising seas: Understanding the science” (PCE 2014), which included the paragraph “The National Institute of Water and Atmospheric Research (NIWA) has projected that in 30 years' time, this level of flooding [*the flooding experienced during the 23 January 2011 storm tide, which had an annual exceedance probability of about 1%*] in Auckland will occur about once every ten years. A few decades later, such flooding is expected to occur every year if the world takes no action to reduce greenhouse gas emissions”. That paragraph was based on calculations undertaken by the author of this report using sea-level measurements at Auckland, and on the most rapidly accelerating “business as usual” SLR trajectory from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

This report extends the early work by calculating the likelihood of occurrence (frequency or return period) of large historical sea-level events with reported coastal hazard impacts (Table A-1), at Auckland, Wellington, Christchurch and Dunedin, and calculating the expected change in frequency of occurrence of these events due to future SLR (Section 3.2).

This report explains the collation and quality checking of New Zealand’s four longest sea-level records at Auckland, Wellington, Lyttelton and Dunedin, and their use to estimate the likelihood of occurrence (frequency) of large historical sea-level events with reported coastal hazard impacts. Calculations were made of the change in frequency of occurrence of these events due to both historical and future SLR.

This report documents the methods used for the sea-level exceedance calculations. NIWA has also supplied Parliamentary Commissioner for the Environment with tables of the percent of high waters exceeding high sea-level thresholds, in digital format.

Historically, SLR since 1900 has caused an approximately linear increase in the frequency of high waters reaching the mean high-water perigean springs elevation. This had led to an approximate doubling since 1900, in the number of days when tides reach the MHWPS “red-alert” level, due to historical SLR. There was a more rapid (approximately quadratic) increase in the frequency of high waters reaching the present-day highest astronomical tide elevation or higher, a result that is consistent with international studies.

Sites with small tidal range, such as Wellington, are more sensitive to SLR. They will experience a greater increase in the number of high waters reaching present-day extreme sea levels than sites with large tidal range such as Auckland. The reason for this is that the tide constitutes most of the sea-level variability in New Zealand (even at the sites with small tides, like Wellington). Thus, extreme sea-levels peak at or close to high tide and the tide makes up a large fraction of the extreme sea level. Where tides are small, SLR forms a greater proportion of the tide compared with other areas with higher tide ranges and therefore the total sea-level height.

The 0.01 AEP sea-level elevation is often adopted as a design “extreme sea-level” for coastal-hazard planning in New Zealand, being a high sea level that occurs infrequently when high tides and storm surges combine. This high sea-level elevation is seldom reached or exceeded in any given year at present-day mean sea level (1% chance), however, projected SLR will noticeably increase the frequency of sea-levels reaching these elevations. Present-day 0.01 AEP sea levels are expected to be reached at least once every year (on average) after a SLR of only 0.16 m at Wellington, and after a SLR of 0.33 m at Auckland. In other words, extreme sea-levels that are expected to be reached only once every 100 years (on average) at present-day MSL, will occur at least annually or more (on average), at all four port sites, after a 0.33 m SLR relative to present-day MSL. A 0.33 m SLR is expected by 2070 under the “business as usual” IPCC RCP8.5 median SLR trajectory, or by 2090 under the low-emissions RCP2.6 median trajectory. SLR of 1 m is considered appropriate for coastal hazard planning purposes over a 100-year timeframe in New Zealand. There will be hundreds of occurrences per year of the present-day 0.01 AEP extreme sea level, at all four sites, if SLR reaches 1 m, with all high tides (100%) in Wellington exceeding that level.

By 2050–2070, depending on location, there will be around one event or more per year that reaches what is presently considered to be an extreme 0.01 AEP sea level, and this will occur for either the fastest *or slowest* IPCC AR5 median SLR trajectories (with the exception of sites with large tidal range such as Auckland, when this might be delayed until 2090 if SLR proceeds slowly). Once this annual occurrence threshold is reached, the number of sea levels exceeding the present-day 0.01 AEP elevation will increase rapidly in time.

Aside from “extreme sea levels”, so-called “lesser extremes”, or “nuisance flooding” events that occur about once per year at present-day MSL will occur about 10-times per year by about 2045, and will increase rapidly in frequency over time thereafter.

This report has focused on the *increasing frequency* of sea-levels reaching high thresholds. In addition, the *depth* of future large storm tides (extreme sea levels) *will be greater*, so that inundation during future infrequent sea level events will be deeper and will reach further inland than the situation presently.

5 Acknowledgements

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6 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.
HAT	Highest astronomic tide.
High water	Measured sea level peak that occurs at or close to high tide. High waters result from the combined effect of all sea-level processes, including tide, SLA and storm surge, some combinations which will result in large and relatively infrequent "extreme" sea levels, but most which represent "normal" sea levels at high tide.
MHWPS	Mean high-water perigean springs. A perigean spring tide occurs when the moon is either new or full (spring tide) and closest to Earth in its monthly orbit (i.e., the perigee). The coincidence of spring tide and perigee peaks about every 7 months.
MHWS	Mean high-water springs.
MSL	Mean sea level – the mean level of the sea relative to a vertical datum over a defined epoch, usually of several years.
Relative sea-level rise	*Relative* sea level is the sea level related to the level of the land. *Relative* sea level changes can thus be caused by absolute changes of the sea level and/or by absolute movements of the land.
SLA	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 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 Measured high sea levels

Table A-1: Measured high sea-level events. AEP > 0.1 were estimated from the empirical high-water distribution (Equation 2-3), AEP ≤ 0.1 were estimated from extreme sea-level models (Section 2.4.1).

Location	Date	Sea-level (m)	Sea level with historic sea-level rise removed (m)	Datum	AEP	ARI (years)	Description	Web link
Auckland	23-Jan-2011	2.38	2.23	AVD-46	1.1-0.5%	88–205	A low-pressure system coincided with a very high tide. The predicted (using UniTide, Foreman et al. 2009) tide was 1.71 m, which is above the 1.55 m MHWPS tide elevation (HAT = 1.91 m), and at approximately the 99th percentile of all high tide peaks. A storm surge of 0.41 m coincided with high tide at the port of Auckland. The 0.41 m storm surge was approximately a 99th percentile of recorded storm surge peaks. The event coincided with a background SLA of nearly 0.1 m (25% of the storm-surge). The weather associated with this event was not particularly remarkable, but the coincidence of the storm surge with a very high tide and high SLA resulted in the highest sea-level on record, and caused considerable inundation, closed motorways and flooded coastal property, with considerable damage (total of $7M in insured losses)[7]. MSL at the time was 0.15 m above AVD-46	http://www.3news.co.nz/nznews/auckland-feels-effect-of-torrential-rainfall-2011012318#axzz3gTfc8gmN http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=10701491 http://www.radionz.co.nz/news/national/66858/more-flooding-predicted-for-auckland-with-high-tide
Auckland	17-Apr-2014	2.07	1.92	AVD-46	40%	1.9	Auckland flooding (Cyclone *Ita*) 17 April 2014. Along Tamaki Drive a significant component of the flooding resulted from local wind-sea (waves) that overtopped the seawall. This wave-driven flooding is not represented by the Port tide gauge from which the exceedance frequencies are derived.	http://www.aucklandcouncil.govt.nz/EN/newseventsculture/OurAuckland/mediareleases/Pages/floodingdebrisandpowercutsasstormhits.aspx http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11239708

[7] http://www.icnz.org.nz/statistics-data/cost-of-disaster-events-in-new-zealand/

Location	Date	Sea-level (m)	Sea level with historic sea-level rise removed (m)	Datum	AEP	ARI (years)	Description	Web link
Auckland	1-Feb-2014	2.00	1.86	AVD-46	80%	0.6	Auckland King tide 1 February 2014 "A beautiful day in Auckland has meant the effects of the king tide were minimised as the high pressure system over the city pushed down on the sea and kept the tides a little lower. A lack of wind also meant the flooding was reduced".	http://www.stuff.co.nz/national/9675124/Tidal-floods-in-Auckland
Wellington	21-Jun-2013	1.29	1.12	WVD-53	1.2%	83	A very strong cold southerly flow swept over the country, bringing very heavy snowfall, heavy rain and gale force winds. Civil Defence emergency operation centres were opened in Wellington, Porirua and Lower Hutt late in the evening of June 20 as the southerly storm got progressively worse. Emergency services and council contractors were kept busy dealing with fallen trees, damage caused to buildings, including roofs being blown off and windows blown in, and other wind-related problems. Properties on Wellington's south coast were worst hit, with residents in Kingston, Melrose, Island Bay and Lyall Bay particularly affected. On 20 June, swells of up to 10 metres were reported in Cook Strait, and with high tide expected at about 1am the next day, there were concerns about possible damage to property and roads along Wellington's south coast. The ferry *Kaitaki* broke its moorings in Wellington Harbour in a 160 km/hr southerly gust. Interislander staff were unable to bring it back into berth, so it was anchored in the harbour temporarily. The Hutt City Council estimated it would cost $100,000 to remove debris washed up on the Petone foreshore when parts of the wall were smashed by the storm surge. Logs and driftwood lay scattered around Marine Parade as far as Eastbourne.	http://hwe.niwa.co.nz/event/June_2013_New_Zealand_Storm
Wellington	7-Jun-2008	1.31	1.11	WVD-53	1.5%	66	Wellington was hit by strong southerlies and driving rain on the evening of the 7th. High winds in the Wellington hills dropped back to about 100 km/hr on the afternoon of the 7th. Wellington harbour was reported to be rough and boisterous.	http://hwe.niwa.co.nz/event/June_2008_New_Zealand_Snow

Location	Date	Sea-level (m)	Sea level with historic sea-level rise removed (m)	Datum	AEP	ARI (years)	Description	Web link
Lyttelton	17-Apr-1999	1.80	1.66	LVD–37	2.1%	46	This was the highest sea level on record at Lyttelton. A high tide (95th percentile) combined with a 0.32 m storm surge. The surge was induced by a large storm that covered much of NZ. A combination of gale force south-westerlies, high rainfall, low air pressure and high tides produced sea flooding on the upper North Island's west coast. On the 16th, the sea level at Bluff rose to 1.83 m above mean sea level. This was the highest level recorded in Bluff Harbour. At Dog Island, there was 0.507 m of storm surge on the 16th. At 1:40pm on the 16th, the Invercargill estuary at the Stead Street Bridge recorded a level of 2.13 m.	http://hwe.niwa.co.nz/event/April_1999_New_Zealand_Snow_and_Marine_Inundation
Lyttelton	27-Jan-1940	1.74	1.72	LVD–37	0.2%	545	This is the highest sea level on record at Lyttelton, once the historical SLR of 0.19 m/ century has been removed. The event consisted of a very high 98th percentile tide, plus a 0.16 m surge superimposed on high background sea-level anomaly of 0.1 m. The extreme-value distribution does not include SLR effects, so this event has the largest ARI, although it was lower than the 1999 event that occurred 59 years later after considerable intervening SLR	
Christchurch	17-May-2011	1.71	1.54	LVD–37	33%	2.5	At Lyttelton a high spring tide coincided with a moderate 0.22 m storm surge compounded by 0.07 m SLA.	http://www.stuff.co.nz/the-press/news/5011651/Riverside-residents-on-edge-at-high-tide
Dunedin	15-Jun-1999	1.76	1.67	DVD–58	1.3%	76	The 15 June 1999 sea-level is the highest on record at Dunedin. It consisted of a very high 1.26 m tide, being higher than 99% of all tides, coinciding with a 0.28 m storm surge and a 0.05 m background sea-level anomaly.	

Location	Date	Sea-level (m)	Sea level with historic sea-level rise removed (m)	Datum	AEP	ARI (years)	Description	Web link
Dunedin	23-Jul-2009	1.60	1.50	DVD–58	34%	2.4	A King Tide event at Dunedin 23 July 2009 that coincided with a storm surge that peaked at 0.31 m.	http://www.odt.co.nz/news/dunedin/66692/tides-flood-roads-erode-dunes
Dunedin	11-Jul-2011	1.53	1.42	DVD–58	83%	0.56	Dunedin 12 July 2011. The article dated 13 Jul 2011 indicated that the high water peaked the day before, but the tide gauge record shows the peak at 00:00 (midnight) beginning 11 Jul 2011. An even higher high water occurred 14:00 13 Jul 2011, although not much different in terms of AEP. This was a high spring tide that coincided with gusty onshore winds that created a considerable local sea that would have further set up the sea-level at the coast. A storm surge of ~0.3 m was measured at the gauge, but coincided with low tide, indicating that waves were probably a significant contributor to the flooding.	http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CBwQFjAA&url=http%3A%2F%2Fwww.odt.co.nz%2Fnews%2Fdunedin%2F168910%2Fharwood-affected-tide-and-wind&ei=5kefVe_dNqXRmAWv34P4Aw&usg=AFQjCNEv1SeNkV6tblW9n4mEafEwG_lExA&sig2=wcfFr8_fPaLLQ-U8_mekIw