Review of Nelson City minimum ground level requirements in relation to coastal inundation and sea-level rise

NIWA Client Report: HAM2009–124
August 2009

NIWA Project: ELF10223

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Executive Summary

Nelson City Council (NCC) is reviewing and updating its Resource Management Plan by October 2009. An aspect of this review is to consider climate-change projections and what changes are needed to the Nelson Resource Management Plan (NRMP) and other NCC policies and engineering quality standards to best manage the effects of coastal inundation in Nelson.

Nelson City Council applied for, and received funding (Advice No. 731-NLCC41), from the Envirolink Fund (Foundation for Research Science and Technology) for NIWA to undertake a review of Nelson's minimum ground level requirements in relation to predicted high-tide events, storm surge and sea-level rise.

Wave set-up was only to be re-assessed for the sheltered estuarine coastline of the Monaco Peninsula in Waimea Inlet. Contributions to inundation levels from river floods or from tsunami were specifically excluded in this review.

The work plan included the following components:

- NIWA to quality-check and analyse available Port Nelson tide gauge data to isolate annual maxima for storm tides and storm surges. Then analyse annual storm-tide maxima directly, and because of the relatively short records, also use an empirical joint-probability approach based on storm surge, seasonal and inter-annual sea-level variability, to determine the Average Recurrence Interval (ARI) for various storm-tide levels for Nelson.
- The wave component for Monaco would be re-assessed based on known wave data and applying an additional contribution of wave set-up and run-up to cover the wave effects on further inundation.
- Assist GIS staff at NCC to prepare preliminary inundation maps over the LiDAR digital elevation model of the Nelson region for various storm-tide and sea-level rise values.
- Once preliminary results for storm-tide levels have been established, NIWA staff to undertake an internal workshop with NCC staff to evaluate the risk (consequences) of extreme coastal water levels and sea-level rise through presentations, dialogue and perusal of the preliminary inundation maps and select appropriate sea-level rise values and associated planning timeframes for the coastal margins around Nelson.
- Following the workshop, prepare a technical report that would be suitable as a companion text supporting the recommendations for any changes to the NCC Resource Management Plan and other policy documents or engineering standards.

The Port Nelson sea level record (1984–2009) was analysed to identify the drivers of Annual Maxima sea level events. In all cases, the Annual Maxima coincided with a high tide that exceeded mean high

water perigean springs (4.35 m Chart Datum). Maximum high water was 4.67 m CD, and only 10% of all tides exceeded 4.23 m. Excluding sea-level rise, the highest extreme sea levels occur when high spring tides coincide with other factors such as high mean-level-of-the-sea, seiche, or storm surge. At Nelson, large positive storm surges occur due to a combination of low atmospheric pressure and strong winds from the north. We estimate that the maximum storm surge at Nelson is in the vicinity of 0.6 m. The extreme-value analysis predicted that a sea level of 5.06 m CD had an Annual Exceedance Probability (AEP) of 0.5%. Adding 0.1 m to account for un-measured variation in MLOS, this gives a maximum design storm tide of 5.16 m CD, or 15.0 m NCC datum, not including long-term sea-level rise.

Following the guidance of the MfE Guidance Manual and Summary (MfE 2008, 2009), sea-level rise values of 0.5 m, 0.8 m and, for some situations of higher risk, 1 m sea-level rise by 2100 were selected to be added to the storm-tide recommendations for minimum ground levels in coastal areas (excluding river flooding). This approach is also in line with the initial starting position for the proposed national Environment Standard (NES) on Sea-level Rise that is about to go out for public consultation. The likely corresponding sea-level rise values at the 2050 juncture (to the ones above for 2100) are 0.23 m, 0.31 m and 0.37 m.

The following Table A contains recommended minimum ground levels in NCC datum with various sea-level rise values that are commensurate with potential consequences for various types of existing or new development. The base value in the table for the present situation is the median 0.5% AEP storm tide of 5.06 m CD, or 14.9 m NCC Datum, plus an extra 0.1 m for variability of the mean level of the sea, which takes it to 15.0 m NCC Datum.

An appropriate sea-level rise component is then added depending on an assessment of future consequences (risk) and possible costs or effort that would be required in adapting to higher sea levels. Risk categories associated with the three sea-level rise values could be: a) 0.5 m sea-level rise for low-value assets such as toilet blocks, playground and recreational facilities and car parking areas or for individual properties in already developed low-lying areas where there maybe adverse drainage and aesthetic impacts on adjoining properties; b) 0.8 m for re-developed residential blocks and commercial properties, and c) 1.0 m for high-value infrastructure assets and new subdivisions that would have a high cost of adaptation when higher sea levels are reached.

An additional wave factor of 0.2 m to allow for wave run-up is recommended for development in the Monaco area. A specific wave set-up and run-up height would need to be determined by a competent coastal practitioner for open-coast environments in Glenhaven, Glenduan, Delaware Bay, Tahunanui Spit and exposed low-lying parts of properties fronting Rocks Road (until such time when NCC is in a position to commission a wave modelling study to provide run-up heights).

Table A: Recommended minimum ground levels for property development or infrastructure plant with different risk profiles (higher risk in darker gray shades). Minimum ground levels are given relative to NCC Datum. [Note: Subtract 9.83 m to get levels relative to Chart Datum or subtract 12.07 m to get levels relative to LINZ Nelson Vertical Datum–1955].

Description	Sea-level components (m)	Low-consequences (m)	Medium-consequences (m)	High-consequences (m)
0.5% AEP storm tide +0.1 m extra MLOS variability	**15.0**	**15.0**	**15.0**	**15.0**
Sea-level rise	*+0.5*	**15.5**		
	+0.8		**15.8**	
	+1.0			**16.0**
Monaco (incl. waves)	*+0.2*	**15.7**	**16.0**	**16.2**

1. Introduction

Nelson City Council (NCC) is reviewing and updating its Resource Management Plan by October 2009. An aspect of this review is to consider climate-change projections and what changes are needed to the Nelson Resource Management Plan (NRMP) and other NCC policies and engineering quality standards to best manage the effects of coastal inundation in Nelson.

Nelson City Council applied for, and received funding (Advice No. 731-NLCC41), from the Envirolink Fund (Foundation for Research Science and Technology) for NIWA to undertake a review of Nelson's minimum ground level requirements in relation to predicted high-tide events, storm surge and sea-level rise.

Wave set-up was only to be re-assessed for the sheltered estuarine coastline of the Monaco Peninsula in Waimea Inlet. Contributions to inundation levels from river floods or from tsunami were specifically excluded in this review.

The outputs from this Envirolink project will assist with sustainable development in the coastal margins of Nelson that includes allowances for the foreseeable effects of climate change and reduces exposure to coastal inundation hazards.

The work plan included the following components:

- NIWA to quality-check and analyse available Port Nelson tide gauge data to isolate annual maxima for storm tides and storm surges. Then analyse annual storm-tide maxima directly, and because of the relatively short records, also use an empirical joint-probability approach based on storm surge, seasonal and inter-annual sea-level variability, to determine the Average Recurrence Interval (ARI) for various storm-tide levels for Nelson.
- The wave component for Monaco would be re-assessed based on known wave data and applying an additional contribution of wave set-up and run-up to cover the wave effects on further inundation.
- Assist GIS staff at NCC to prepare preliminary inundation maps over the LiDAR[1] digital elevation model of the Nelson region for various storm-tide and sea-level rise values.

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[1] Light Detection And Ranging – an aircraft-mounted scanning system using pulsed laser beams to obtain accurate ground topography (often down to an accuracy of 0.15 m)

- Once preliminary results for storm-tide levels have been established, NIWA staff to undertake an internal workshop with NCC staff to evaluate the risk (consequences) of extreme coastal water levels and sea-level rise through presentations, dialogue and perusal of the preliminary inundation maps and select appropriate sea-level rise values and associated planning timeframes for the coastal margins around Nelson.
- Following the workshop, prepare a technical report that would be suitable as a companion text supporting the recommendations for any changes to the NCC Resource Management Plan and other policy documents or engineering standards.

The workshop between NCC and NIWA at Nelson (2 July 2009) agreed that the NIWA technical report should:

1. provide for a planning time frame to 2100 (but also provide examples of interim levels for perhaps 2050 just for illustrative purposes);

2. establish scenarios in relation to a range of possible sea-level rises above storm-tide levels of 0.5, 0.8 and 1.0 metres;

3. include a commentary and guidance on projected sea-level rise beyond 2100;

4. add 0.1 m to storm-tide levels for variations in longer-period mean sea level variations not captured in the short Port Nelson record;

5. due to uncertainties over changes to storms in central New Zealand by 2100, no additional factor is applied for the effect of climate-change on storm surges (where winds and low-pressure storm intensities could be affected by changes in climate);

6. not include an additional safety or freeboard factor in the recommendations for minimum ground levels (as distinct from minimum floor levels) – if required this can be added in later by NCC staff to the RMP and Engineering Standard;

7. indicate that generic minimum ground recommendations would not be applicable to development in the exposed open-coast margins of Glenduan, exposed parts of Rocks Road and Tahunanui. At these locations, specific applications would need to include an additional analysis of wave set-up and

run-up, to be combined with the analysis of sea levels contained in this report. For Monaco, the workshop agreed that the existing 0.2 m wave factor in the current NCC Engineering Standard should be retained;

8. draw attention to need for "low regrets" adaptation options for building floor levels compared to ground levels.

2. Datums

Nelson City (and similarly Christchurch) historically defined a drainage datum that was set well below low tide to ensure Reduced Levels (RL) were always positive values even for pipe networks in the ground. The NCC Datum is 9.83 m below the Chart Datum (approximately the Lowest Astronomical Tide) at Port Nelson, as shown in Figure 2–1. In recent years (1996–2007), the actual mean level of the sea (MLOS) has been at an average of 12.14 m above NCC Datum or 2.31 m above Chart Datum (CD) as determined by Land Information NZ (LINZ).[2]

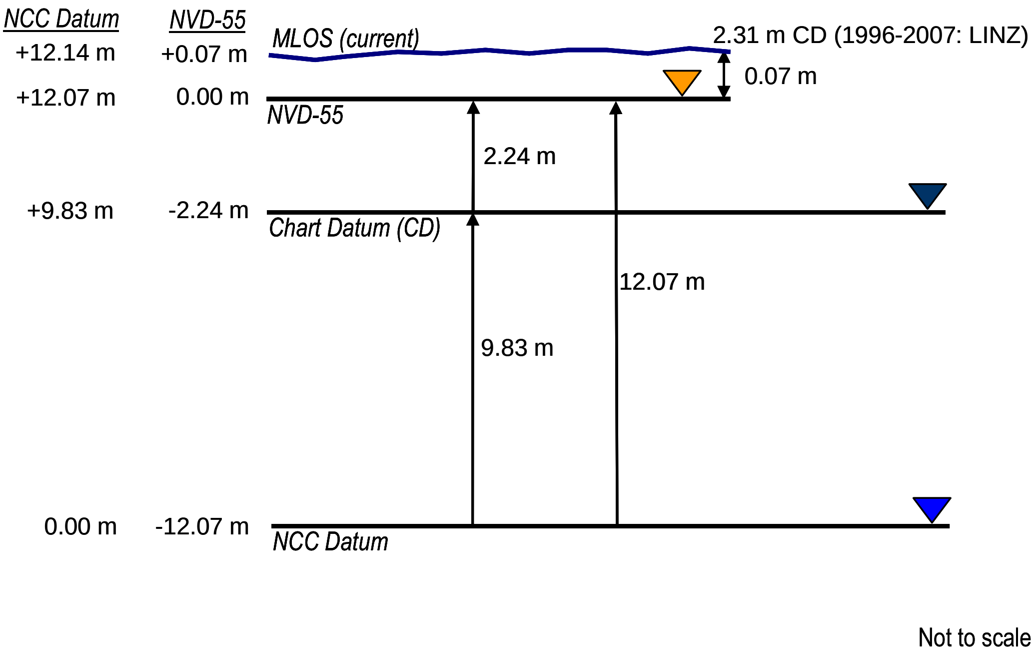

Figure 2-1: Nelson City: conversions between the various local vertical datums.

The LINZ local vertical datum, Nelson Vertical Datum-1955 (called NVD-55 in this report), was set up in 1955 based on sea level measurements from 1939 to 1942. Since that time, sea levels have risen, with MLOS now at 0.07 m relative to NVD-55. NVD-55 is 2.24 m above Chart Datum at Port Nelson.

Note: NVD-55 is used by Tasman District Council for defining ground elevations.

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[2] http://www.linz.govt.nz/hydro/tidal-info/tide-tables/tidal-levels/index.aspx

3. Sea level

There are a number of meteorological and astronomical phenomena involved in the development of an extreme sea level event. These processes can combine in a number of ways to create inundation of low-lying coastal margins. The processes involved are:

- Mean level of the sea (MLOS)
- Astronomical tides
- Tidal residual
- Wind set-up
- Inverse-barometer (IB) effect
- Wave set-up
- Wave run-up

Storm surge = wind set-up + IB

The mean level of the sea describes the variation of the non-tidal sea level on longer time scales ranging from a monthly basis to decades due to climate variability including the effects of El Niño–Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO) patterns on sea level, winds and sea temperatures. In the context of climate change, sea-level rise is presented relative to MLOS over the period 1980–99.

The astronomical tides are caused by the gravitational attraction of solar bodies, primarily the sun and the Earth's moon. In New Zealand the astronomical tides have by far the largest influence on sea level, followed by storm surge (in most locations), which is caused by a combination of wind set-up and the inverse barometer[3] effect.

The tidal residual is a term that refers to short-period (high-frequency) oscillations in sea level at periods of < 6 hours. These can be caused by seiche[4] within a harbour or

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[3] Change in sea level elevation due to changes in atmospheric pressure. The relationship is "inverse" because as the pressure decreases ("barometer" drops), the sea level rises.

[4] Seiches are waves that move up and down, but not forward like wind waves or swell–which is why they are also called standing waves. They occur in enclosed or semi-enclosed basins such as lakes, harbours, bays and are caused by external forcing e.g., strong winds, changes in pressure, earthquake motion. Everyday examples occur in a bathtub or in a cup of tea that has been bumped.

basin, by interactions between the bathymetry and tides, or a number of other processes.

Wind set-up describes the “piling up” of water against the coast by an onshore (or alongshore if the coast is to the left of the wind) prevailing wind. The effect of wind stress on the sea surface increases inversely with depth and therefore is most important in shallow water (Pugh, 2004). The inverse-barometer effect describes the change in sea-surface elevation as a response to changes in atmospheric pressure: more specifically sea level temporarily rises in a response to decreasing atmospheric pressure and decreases as atmospheric pressures increase. The combined effect of wind set-up and inverse barometer produce “storm surge” events. Storm surges generally only have consequential effects when they coincide with high tides.

In the open oceans, there is a direct isostatic[5] relationship between sea level and barometric pressure, known as the inverted barometer (IB) response: 1 hPa decrease in pressure results in a 10 mm increase in sea level (and vice versa). However, isostatic conditions rarely apply (particularly around islands such as New Zealand) and the relative importance of the IB-induced pressure wave interactions with the coastal landmass determines how applicable the IB response is. An analysis of tide gauge records at 15 locations around New Zealand showed that Nelson had a moderate IB response, explaining 59% of sea level change associated with weather systems (Goring 1995). This shows that on average, up to 40% of weather-related sea level variation at Nelson is explained by non-IB effects, such as wind set-up for example. The barometric factor at Nelson was 0.78 (Goring 1995), which means that the average IB response is 0.78 of the isostatic response, i.e., 1 hPa decrease in pressure results in a 7.8 mm increase in sea level (and vice versa). Thus an air pressure of 975 hPa might be expected to result in a 0.30[6] m storm-surge height relative to the mean average air pressure of 1014 hPa for Nelson. We might expect up to 0.20[7] m of non-IB related storm surge, caused by such things as wind set-up, leading to a total storm surge of about 0.50 m (= 0.30 m + 0.2 m) in “set–up favourable” wind conditions. This example shows the typical average ratio between IB and wind set-up response based on the analysis of Goring (1995), but in reality the response will be unique for each passing low-pressure system.

Waves also raise the effective sea level at the coastline by two mechanisms. Wave set-up is the increase in mean sea level through the transfer of excess momentum from

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[5] An isostatic sea level response to changing atmospheric pressure occurs when an atmospheric pressure change results in an exactly equal pressure adjustment in the water column, thus 1 hPa change in pressure results in a 10 mm inverse response in sea level.

[6] IB response = (1014 – 975 hPa) × 10 mm/hPa × 0.78 = 296 mm.

[7] Wind set-up = 296 mm × 60% / 40% = 198 mm.

organised wave motion in the surf zone (Longuet-Higgins and Stewart 1962). Set-up due to waves is the result of a constant raised elevation of sea level when breaking waves are present. Wave run-up is the maximum vertical extent of wave "up-rush" on a beach or structure above the still water level, and thus constitutes only a short-term fluctuation in water level relative to set-up and storm surge time scales (Komar 1998).

In this report we do not consider the effects of waves, which are localised within the surfzone or adjacent to seawalls at the shoreline. We focus on the "storm tide" that results from a combination of MLOS, tide, storm surge and tidal residual, and which can be resolved from the sea-level record at Port Nelson.

3.1 Sea level data

Sea level is measured at the Port of Nelson tide gauge. The zero of the tide gauge coincides with the local Chart Datum, which is 9.83 m above NCC datum (Figure 2-1). The raw dataset contained some bad data, with sea level "spikes" and offsets in both sea level and time (e.g., change-over to daylight saving). Pre-processing to "clean" the data was therefore required before using it for analysis. A cleaned dataset of 1-hourly-spaced sea level was supplied by LINZ for the period 1 July 1984 to 15 May 1996, but data measured after this was cleaned for the purposes of the study. Since the time interval of recording changed over time, the data was interpolated to a 15-minute interval throughout before being analysed. Sea level records exist prior to 1984, but their reliability is questionable (Murray McGuire, *pers. comm.*).

A time series of the cleaned sea level data are plotted in Figure 3-1. Large gaps in the record are evident, but the record is continuous from 2001 onward, apart from some small gaps. The largest events measured in each calendar year, known as "Annual Maxima", are plotted as red circles, and the red circles have been filled if the data record spanned at least ¾ of the year. Thus the filled Annual Maxima can be thought of as "reliable" values, whereas the hollow Annual Maxima are "unreliable", since it is likely that a higher sea level occurred during those years at a time when the sea level was not recorded (and also possible in years with <75% data coverage). The gaps in the record create problems for extreme value analysis; this is discussed in Section 4.

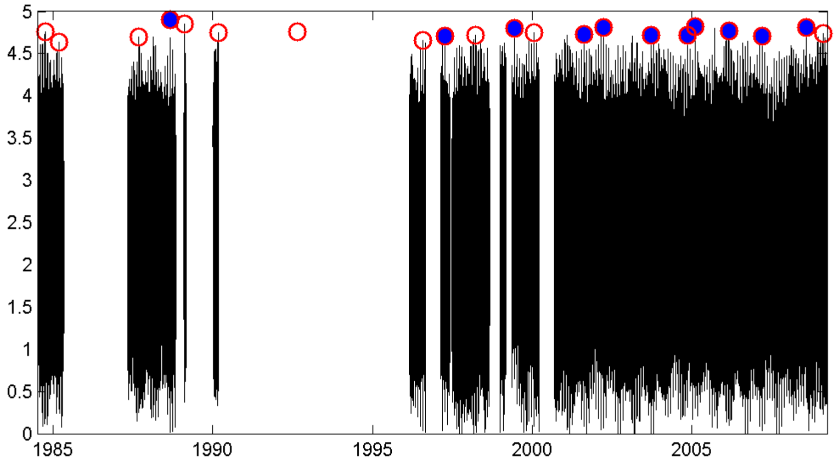

Figure 3-1: Time series of sea level height (in metres relative to Chart Datum) measurements at Port Nelson 1984–2009. Annual Maxima are marked by a red circle, for each calendar year in which measurements were made. The circle is filled if the data coverage for the calendar year was > 75%.

Figure 3-2 shows a power spectrum of the sea level record. The power spectral density on the *y*-axis is equivalent to the energy of the sea level oscillation[8]. Peaks in the power spectrum occur at particular frequencies (or periods; period = 1/frequency). In Figure 3-2 the frequency labels on the *x*-axis have been converted into period in hours to more easily relate the spectral energy peaks to the period of the processes (e.g., tides) that drive them. The largest spectral energy peak is associated with the semi-diurnal (occur twice a day) tides that have a period of oscillation of about 12-hours. This demonstrates that the semi-diurnal tides are responsible for most of the sea level variation at Nelson. Smaller peaks are associated with diurnal (occur once a day) tides, and short period over-tides and seiche within Tasman Bay. There is considerable energy at longer periods associated with storm surge, but because storm surge is not a regular sea level oscillation there are no clear peaks and the storm surge energy is smeared across a range of periods (frequencies) in the power spectrum.

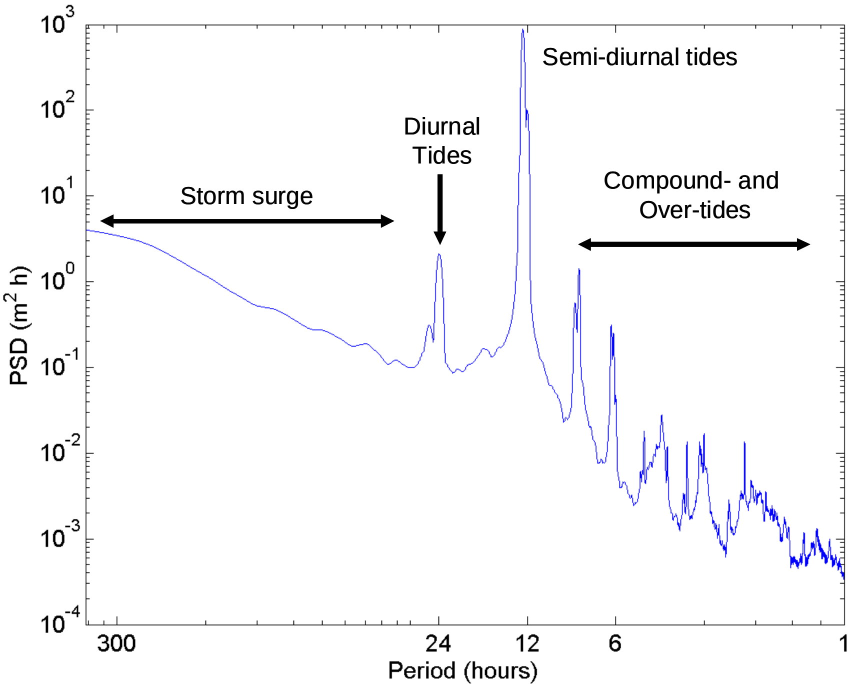

Figure 3-2: Power spectral density (PSD) of sea level versus period of oscillation (period = 1/frequency).

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[8] Oscillation refers to the vertical movement of sea level, up and down, at a *regular* period (or frequency).

Tidal harmonic analysis was undertaken on an annual basis following (Pawlowicz et al. 2002). The predicted water-level variation due to tides was then subtracted from the total sea levels to give the residual non-tidal component of water-level variation. Wavelet filters were then applied to the non-tidal sea level component to decompose it into the mean level of the sea (MLOS = the component of sea level variation with a period of greater than 1-month), and the storm surge (SS = the component of sea level variation having energy in the 1–16 day band). Figure 3-3 shows the tide, MLOS and storm surge components of sea level.

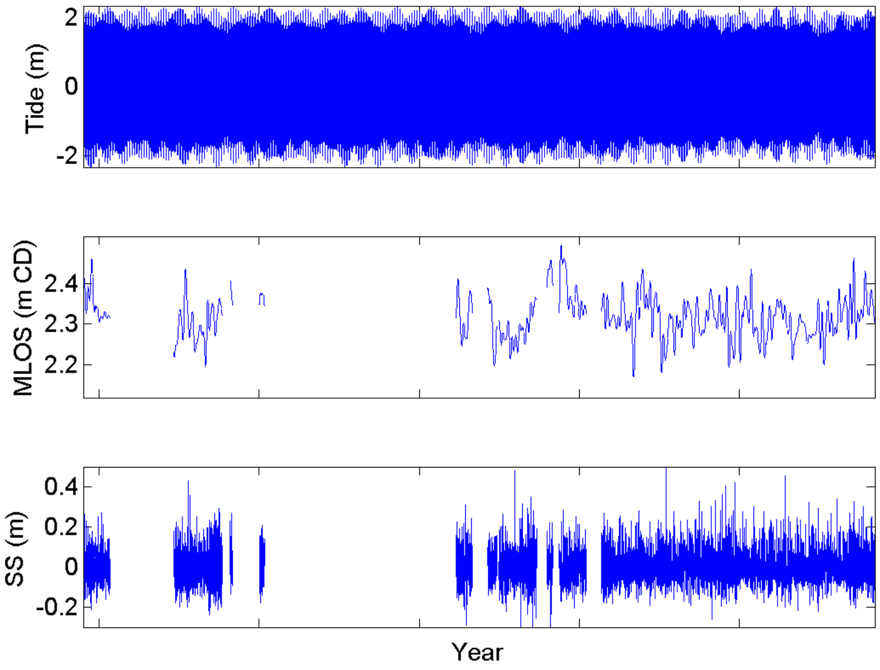

Figure 3-3: Components of sea level. Top plot: astronomical tide predicted from tidal harmonic analysis of the sea level record. Middle plot: Mean-level-of-the-sea (MLOS). Lower plot: Storm surge (SS).

Figure 3-4 shows the high tide exceedance curve for Nelson. The plot was generated by predicting 100-years of high tides using the tidal constituents determined from tidal harmonic analysis of the gauge record, and plotting the cumulative exceedance of the high tides. It excludes weather- and climate-related effects including sea-level rise. Maximum high water was 4.67 m CD, and only 10% of all tides exceeded 4.23 m.

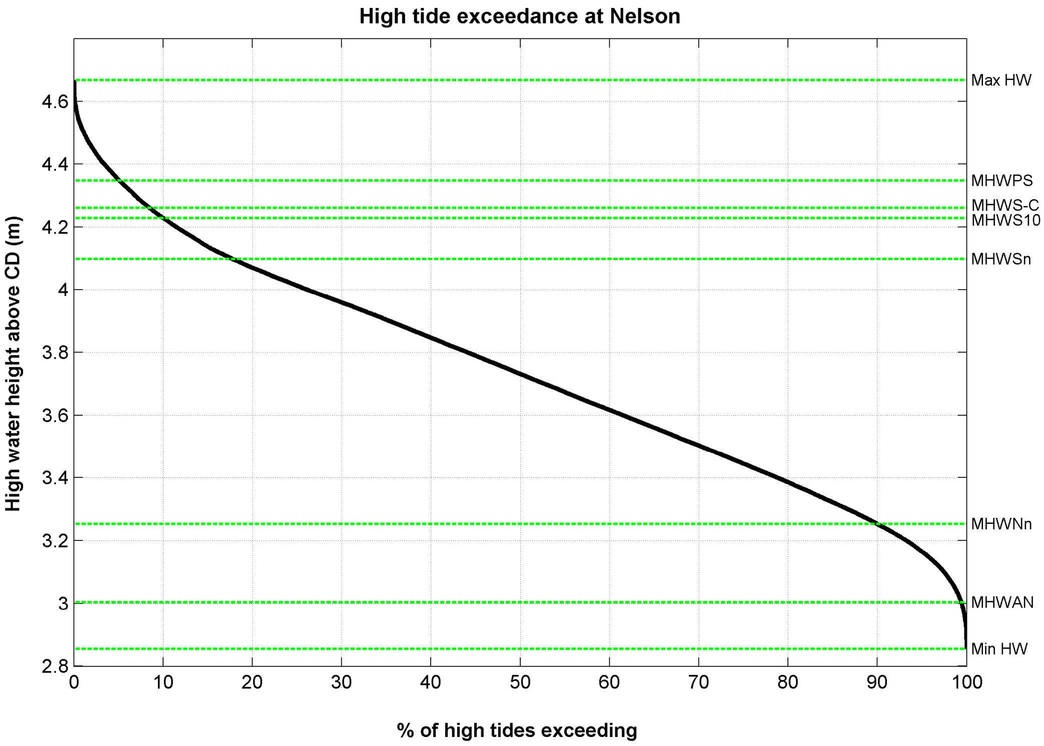

Figure 3-4: High tide exceedance at Port Nelson relative to Chart Datum. Max HW = maximum high water; MHWPS = mean high water perigean spring ($M_2 + S_2 + N_2$); MHWS-C = published cadastral definition of mean high water spring from LINZ; MHWS-10 = mean high water spring height exceeded by 10% of all tides; MHWSn = mean high water spring nautical ($M_2 + S_2$); MHWNn = mean high water neap nautical ($M_2 – S_2$); MHWAN = mean apogean neap ($M_2 – S_2 – N_2$); Min HW = minimum high water.

Figure 3-5 shows a similar plot for the measured storm surge, but relative to the mean level of the sea. It is seen that although some large storm surges (> 0.2 m) did occur, the great majority of surges were small. For example, the chances of a storm surge > 0.2 m in height are much lower (0.9%) than the chances of a 4.35 m perigean spring tide (5% of all high tides).

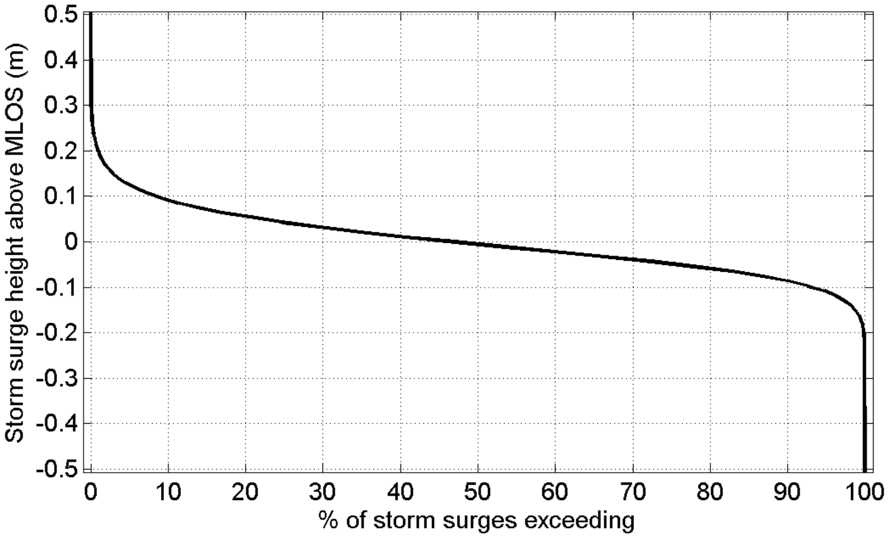

Figure 3-5: Cumulative exceedance plot of storm surge at Port Nelson relative to the mean level of the sea at the time of the event.

3.2 Characteristics of sea level Annual Maxima

The time series of Annual Maxima from several years of measurement can be extrapolated to provide estimates of the probability of occurrence of extreme sea levels of various heights. The Annual Maxima make up a series of extreme values for each calendar year that incorporate seasonal effects. For example, large storm surges might be more common in winter. Thus it is useful to examine the Annual Maxima in more detail. Table 3-1 lists the Annual Maxima from the gauge record, along with the coincident predicted tide height, storm surge and mean-level-of-the-sea. Years for which data coverage was at least ¾ are marked in bold, these are the “reliable” Annual Maxima. Also listed is the sea level recorded during the 19 March 1957 storm for which photographic evidence of waves washing across the road at Rocks Road exists (Figure 4–4). The “highest recorded sea level” of 5.12 m (C.D.) is also listed. The timing and origin of measurement and the reliability of this value are unknown (Murray McGuire, *pers. comm.*). In Section 4 we examine its probability of occurrence according to the extreme value analysis.

Table 3-1: Annual Maximum sea levels (in metres relative to Chart Datum) at Port Nelson, including the tidal and storm surge components. Years with greater than 75% data coverage are highlighted, years with no data are left blank.

Year	Date	Sea level (m CD)	Tide (m CD)	Storm surge height (m)	MLOS (m)
	Unknown	**5.12**			
1957	**19 March 1957**	**4.81**			
1984	27 September 1984	4.76	4.44	0.03	0.17
1985	8 March 1985	4.64	4.50	0.05	0.08
1986					
1987	8 September 1987	4.70	4.41	0.17	0.00
1988	30 August 1988	4.90	4.64	-0.01	0.28
1989	8 February 1989	4.85	4.58	0.05	0.13
1990	28 February 1990	4.75	4.39	0.11	0.22
1991					
1992	29 August 1992	4.76			
1993					
1994					
1995					
1996	3 August 1996	4.65	4.47	0.15	-0.04
1997	8 April 1997	4.71	4.46	0.15	0.08
1998	29 March 1998	4.72	4.59	0.29	-0.14
1999	15 June 1999	4.80	4.51	0.15	-0.02
2000	24 January 2000	4.75	4.38	0.08	0.25
2001	19 August 2001	4.72	4.49	0.13	0.10
2002	30 March 2002	4.81	4.54	0.11	0.10
2003	28 September 2003	4.72	4.47	0.17	0.09
2004	15 November 2004	4.72	4.34	0.35	0.10
2005	11 February 2005	4.82	4.51	0.11	0.19
2006	2 March 2006	4.77	4.61	-0.06	0.19
2007	21 March 2007	4.70	4.63	-0.04	0.16
2008	2 August 2008	4.81	4.36	0.30	0.01
2009	12 February 2009	4.74	4.39	0.15	0.13

In all cases, the Annual Maxima coincided with a high tide that exceeded mean high water perigean springs (4.35 m). High spring tides dominate the Annual Maxima because they occur relatively regularly compared to large storm surges, and because the tides are so much larger than the storm surge. In most cases the storm surge component was relatively small or even negative. Variation in the mean-level-of-the-sea was of similar magnitude to storm surge. This is not to say that storm surge is unimportant, nor that it should be neglected during extreme value analysis, but it does demonstrate that large storm surges rarely coincide with high spring tides.

Figure 3-6 shows a time series of the measured sea level, the predicted tide and the storm surge, coinciding with the Annual Maximum on 21 March 2007. It is seen that the Annual Maximum was dominated by the tide. A relatively large storm surge of ~0.3 m had occurred earlier in the month, but it coincided with a neap tide.

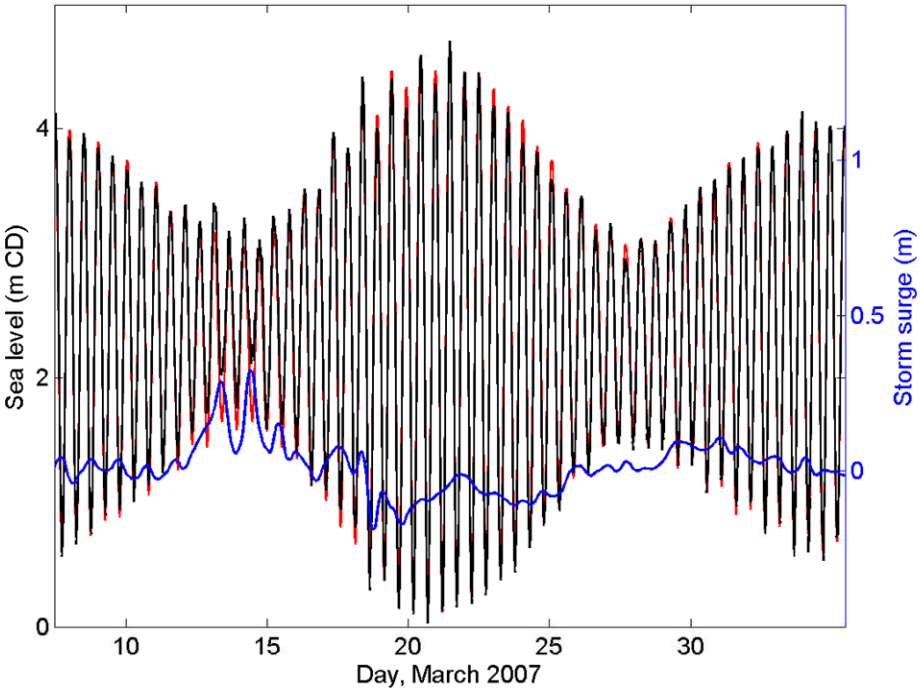

Figure 3-6: Time series of sea level, coinciding with the 2007 Annual Maximum. Predicted tide is plotted in red, with the measured sea level over-plotted in black. The storm surge component of sea level is plotted in blue, on a different scale (right-hand side).

Figure 3-7 and Figure 3-8 show (at different magnification) time series of the measured sea level, the predicted tide and the storm surge, coinciding with the Annual Maximum on 15 November 2004. In this case a large storm surge did coincide with a spring tide. Although a spring tide, the predicted tide was still 0.33 m below highest astronomical tide. This case demonstrates how a rare coincidence of a high storm surge and a high tide can cause extreme high water levels.

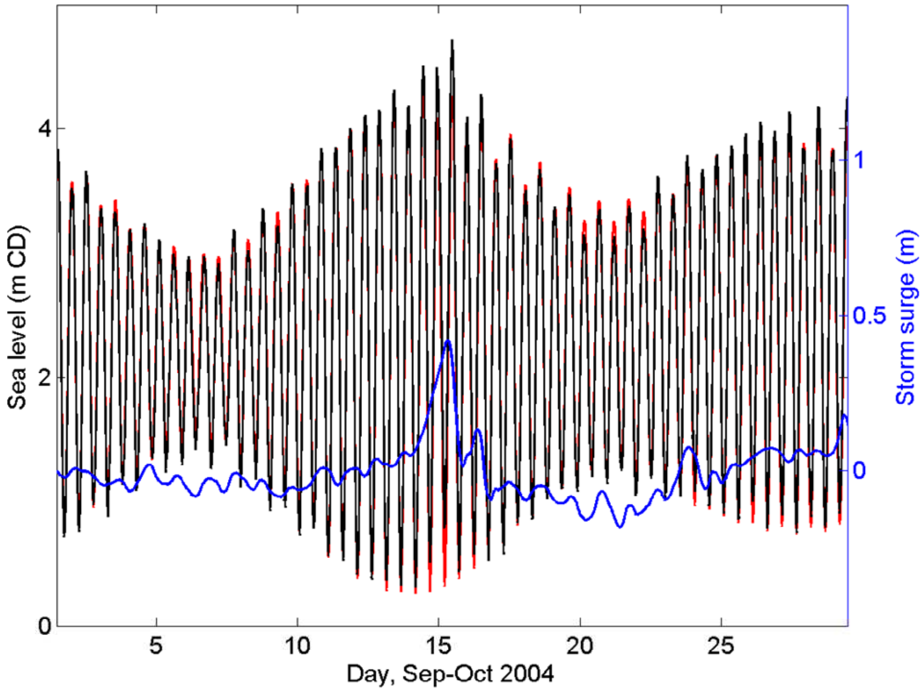

Figure 3-7: Time series of sea level, coinciding with the 2004 Annual Maximum. Predicted tide is plotted in red, with the measured sea level over-plotted in black. The storm surge component of sea level is plotted in blue on a different scale.

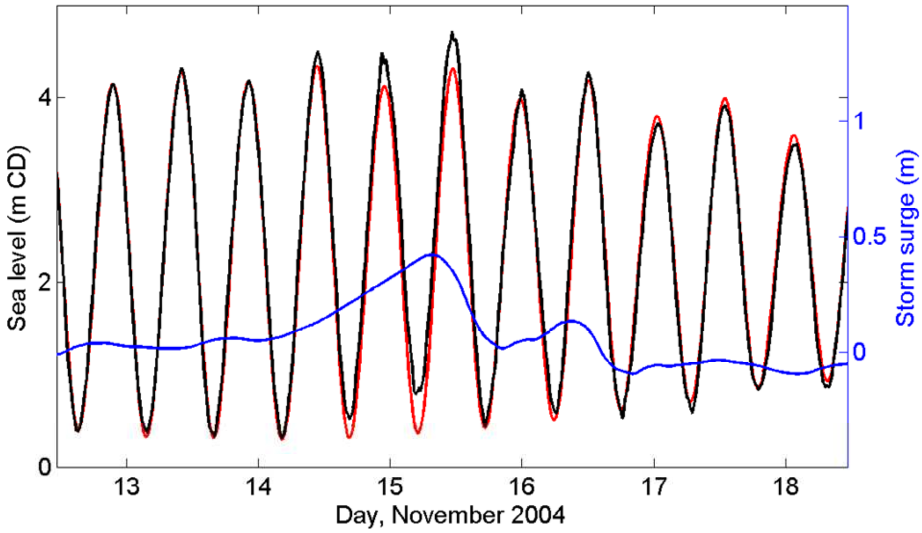

Figure 3-8: Time series of sea level, coinciding with the 2007 Annual Maximum. Predicted tide is plotted in red, with the measured sea level over-plotted in black. The storm surge component of sea level is plotted in blue.

Table 3-2 matches the largest 6 storm surges identified from the sea level gauge, with coincident meteorological information from Nelson airport. There is a strong correlation between the weather patterns and the storm surge. These large positive storm surges appear to occur due to a combination of low atmospheric pressure (high inverse-barometer effect) and strong winds from the north that would act as a bulldozer, pushing surface water onshore toward Nelson. The split between IB and non-IB is about 60% and 40% respectively, as observed on average by Goring (1995), although the exact response varies from storm to storm. Based on an expected minimum atmospheric pressure of 970 hPa, and an isostatic IB response constituting 70% of the total storm surge, we estimate that the maximum storm surge at Nelson is in the vicinity of 0.6 m, which is similar to the sum of the largest IB plus the largest Non-IB from all events in Table 3-2.

Table 3-2: Details of the six largest measured storm surges. MSLP = mean sea-level pressure; IB = inverse barometer; non-IB are storm-surge contributions from other sources than IB. Wind and MSLP data are from Nelson Airport.

Date	Storm surge (m)	MSLP (hPa)	IB (m)	Non-IB (m)	Wind speed (m/s)	Wind direction
19 September 2002	0.51	984	0.29 (57%)	0.22 (43%)	18	30
12 June 2006	0.46	977	0.36 (78%)	0.10 (22%)	13.4	40
13 October 1987	0.43	987	0.26 (60%)	0.17 (40%)	16.5	10
15 November 2004	0.42	983	0.3 (71%)	0.12 (29%)	16	20
1 July 1998	0.35	994	0.19 (54%)	0.16 (46%)	10.8	40
22 January 2008	0.34	993	0.2 (59%)	0.14 (41%)	17	30

4. Extreme storm-tide levels

Extreme storm-tide levels are usually predicted by fitting an extreme-value model such as the generalised extreme value model, to a subset of independent maxima from an existing sea-level record (Coles 2001). In this way the very largest events in the record are extrapolated to estimate even larger events that might occur in the future.

The accuracy of the extreme sea level predictions depends on:

1. the quality of the input data, including: (a) the accuracy of the measured or simulated sea level maxima; and (b) suitable historic coverage—the longer the available record the more reliable the estimates. Increased reliability results from improved statistical precision of the estimates and from decreased error associated with climate variability; and

2. the degree of fit between the "true" distribution of the sea levels, and the fitted statistical distribution (e.g., Generalised Extreme Value or GEV model) used to extrapolate to the extreme values.

As seen in Figure 3-1 there are many gaps in the sea level record at Nelson. In the 25 years since 1984 there were just 11 years where data coverage was > ¾. As a general rule, extreme-value estimates can be calculated for ARI[9] of up to 3-5 times the record length. In this case 11 years of data should give reliable estimates for ARI of up to 30-50 years.

Figure 4-1 shows a traditional extreme-value analysis based on the 11 "reliable" Annual Maxima, supplemented with the 19 March 1957 storm tide. The model fit is seen to unbounded (i.e., it continues to increase with decreasing AEP[10]), which is physically unrealistic, since we know that the size of a storm tide is physically limited. Furthermore, the confidence intervals are wide even at 0.1 AEP (10-year ARI), and we have very little confidence in longer-term (e.g., 0.01 AEP, 100-year ARI) predictions from this analysis.

If we include all the Annual Maxima in Table 3-1, even from partially complete years, then we get the fit shown in Figure 4-2. The curve is very strongly bounded,

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[9] Average recurrence interval – a given (high) sea level would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years, e.g., a 1 in 100-year sea level.

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

suggesting that a sea level of 5 m CD is highly unlikely, with tight confidence intervals. Unfortunately, because many of the Annual Maxima are misrepresented by lower values than would likely have been measured during a full year's record, the statistical theory that underlies the GEV model has been violated and the curve shown in Figure 4-2 cannot be trusted. It is probable that the very strongly bounded nature of the fit results from these misrepresented Annual Maxima.

The sea level record is therefore not sufficient to successfully undertake an extreme-value analysis using Annual Maxima. The following messages arise:

- Reliable extreme value estimates require a high-quality dataset.
- To reliably capture the Annual Maxima the gauge must sample continuously with no gaps in record (or at least none during storm tides).
- The gauge needs to be accurate.
- The gauge should be surveyed in to datum and regularly checked for drift.
- The longer the record the better, extreme-value analysis can typically provide reliable estimates out to about 3-5 times the record length.

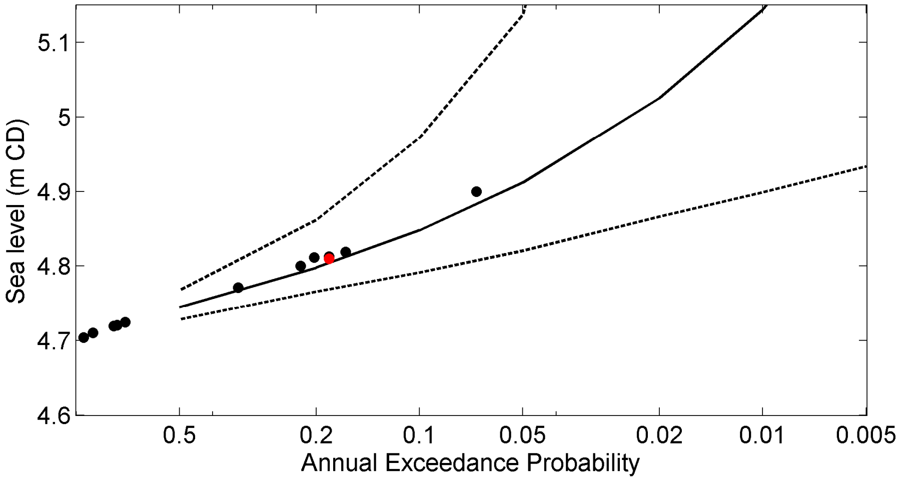

Figure 4-1: Generalised extreme value model including 95% confidence intervals fit to 11 Annual Maxima, plus the 19 March 1957 storm tide (marked red).

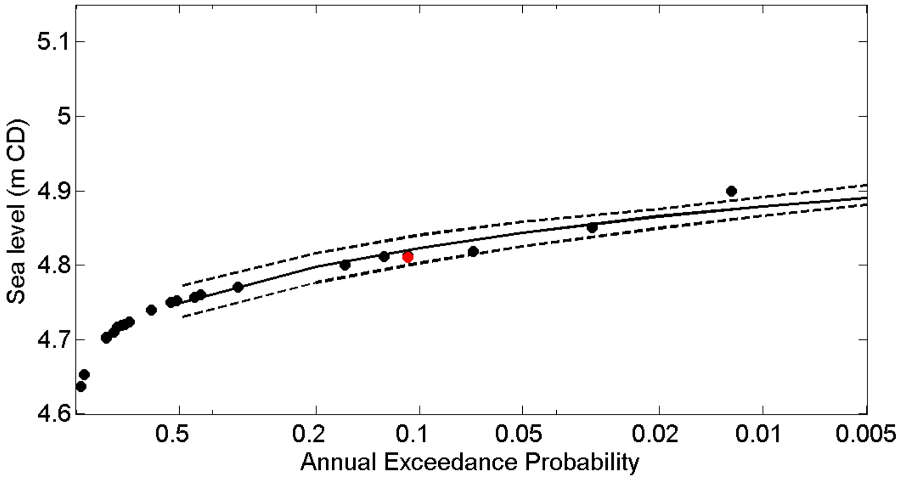

Figure 4-2: Generalised extreme value model including 95% confidence intervals fit to all 21 Annual Maxima in Table 3-1, plus the 19 March 1957 storm tide (marked red).

Fortunately, a new empirical simulation technique (EST) has recently been developed for predicting extreme sea levels from short sea-level data records (Goring et al. submitted; see Appendix for description). The technique assumes that tide and storm surge are independent, which is a reasonable assumption to make for the open-coast location of the Port Nelson tide gauge. The technique breaks the sea level record down into its various components (tide, storm surge, MLOS, tidal residual) and recombines them using a bootstrapping technique to estimate the annual exceedance probability for a range of sea levels. The technique simulates many thousands of years of data, so it includes even very rare coincidences of high spring tides with large storm surges, which are unlikely to be measured during a short record. The extreme-value analysis from the EST is plotted in Figure 4-3. The EST agrees with the traditional approach for AEP of 0.5–0.05, which are in the approximate range of probabilities for which we would expect reliable estimates from the traditional approach, given the number of reliable Annual Maxima. At lower AEP the two curves depart, with the EST giving more believable sea level estimates within a practical confidence interval. The results of the EST analysis are included in Table 4-1.

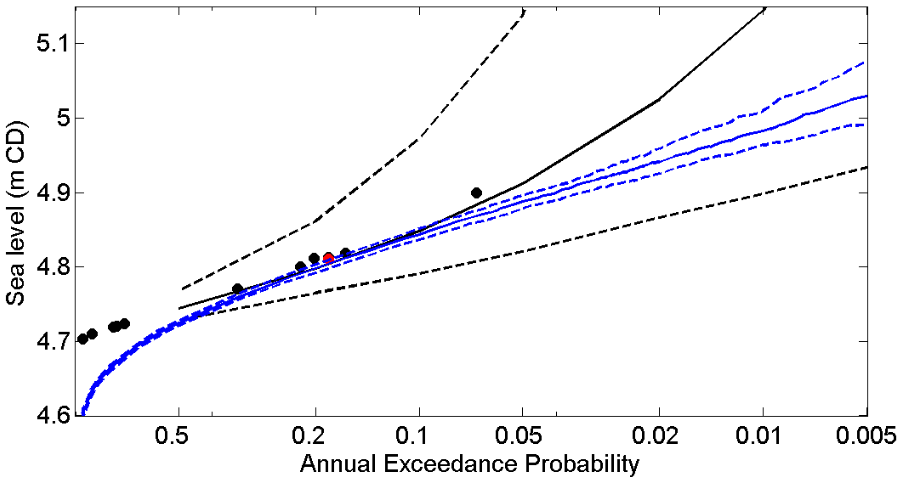

Figure 4-3: Extreme-value curve including 95% confidence intervals estimated using the empirical simulation technique (blue), over-plotted on the analysis shown in Figure 4-1.

Table 4-1 shows that there is a 0.5% chance of a sea level of 5.06 m (or higher) occurring in any given year. In other words, a sea level of 5.06 m or higher would be expected to occur once, on average, every 200 years. Based on the EST analysis, the "unknown" event (Table 3-1) of magnitude 5.12 m CD has an AEP of 0.002, and an ARI of 420-years. The analysis does not rule out the possibility that a sea level of 5.12 m CD did occur, but suggests that a sea level of this height would be very unlikely to occur again soon.

The EST makes use of sea level components filtered out of the measured data. The measured range of MLOS was about ±0.15 m, but this would be expected to rise to ±0.25 m over a long period, due to the combined effect of IPO and ENSO and seasonal sea level variations. Therefore we recommend adding a further 0.1 m to the values in Table 4-1 for design purposes.

Table 4-1: Extreme storm-tide estimates for Nelson, using the Goring et al. (submitted) method. The estimates are given in metres relative to Chart Datum, for present-day MLOS.

AEP	**0.5 (50%)**	**0.2 (20%)**	**0.1 (10%)**	**0.05 (5%)**	**0.02 (2%)**	**0.01 (1%)**	**0.005 (0.5%)**
ARI	**2**	**5**	**10**	**20**	**50**	**100**	**200**
Minimum	4.72	4.80	4.84	4.89	4.94	4.96	5.01
5% c.i.	4.73	4.80	4.85	4.89	4.94	4.99	5.02
Median	**4.73**	**4.81**	**4.85**	**4.90**	**4.96**	**5.01**	**5.06**
95% c.i.	4.73	4.81	4.86	4.91	4.98	5.04	5.12
Maximum	4.73	4.81	4.86	4.91	4.99	5.07	5.13

4.1 Comparison with existing Nelson City Council Engineering Standards 2003

The minimum ground and floor level requirements in Section III-10 of Nelson City Council Engineering Standards 2003 are based on a “tidal surge level at year 2050” of 15.30 m (NCC datum). This value was obtained by using a “building block” approach as outlined in Table 4-2. “Building block” approaches are extremely conservative, for example the assumption in Table 4-2 is that the maximum spring tide and maximum storm surge height will coincide. Furthermore, the building block approach used in Table 4-2 has omitted other variables that also contribute to sea level, such as MLOS, with a range of ±0.25 m around New Zealand, and the tidal residual which includes a seiche in Tasman Bay with an amplitude of up to ~0.3 m (Goring 2004). Inclusion of these in the building block approach would have raised the storm tide level at 2050 to 5.75 m (without including the 0.3 m of sea-level rise). In the context of the extreme-value analysis (Figure 4-3) a value of 5.75 m CD is entirely improbable, i.e., the building block approach completely misrepresents the physics.

In comparison the EST predicted a 0.5% AEP sea level of 5.06 m CD. Adding 0.1 m to account for un-measured variation in MLOS, this gives a maximum design storm tide of **5.16 m CD**, or **15.0 m NCC datum**, not including long-term sea-level rise. This is remarkably similar to the building block approach presented in Table 4-2, minus the sea-level rise component. Thus, although a different (and not scientifically robust) method was used to develop the design storm tide in the Nelson City Council Engineering Standards 2003, the value agrees closely with our latest estimate.

Table 4-2: Predicted maximum "tidal surge level at 2050" showing the values of the various sea level components added into the estimate used as the basis for the current NCC Engineering Standards (2003).

Description	Tide gauge (m; Chart Datum)	Water level (m; NCC datum)
Maximum predicted spring tide	4.6	14.4
Maximum storm surge expected	+ 0.6	+ 0.6
Mean global sea-level rise at 2050	+ 0.3	+ 0.3
Maximum storm tide level at 2050	**= 5.5**	**= 15.3**

4.2 Wave set-up and run-up

Wave setup is the super-elevation of the mean water level at the shoreline resulting from waves breaking at the coast. Wave setup was first recognized as a natural hazard during a hurricane in 1938 that struck the east coast of the United States. It was observed that the maximum mean water level was about 1 m higher in a high-wave-energy environment where wave energy was dissipated as surf, compared to a nearby low-wave-energy environment. It is now recognised that wave setup is a key contributor to coastal flooding and storm damage in some locations. When coinciding with high tide and storm surge, wave setup can further raise the mean sea level at the shoreline contributing to structural damage, beach erosion, and coastal flooding.

Wave run-up is the maximum vertical extent of wave "up-rush" on a beach or structure above the still water level, and thus constitutes only a short-term fluctuation in water level relative to set-up and storm-surge time scales. Wave run-up may over-top seawalls, beach berms or coastal roads, effectively "pumping" water into and flooding lower-lying land (and or buildings) behind.

Wave set-up and run-up are dependent not only on the offshore wave conditions, but are also strongly dependent on the local shape of the seabed and the profile of the local beach and natural coastal barrier or seawall. Therefore, locations in close proximity can have quite different wave set-up and run-up resulting from the same offshore wave conditions, due to local interactions with the coastal margin. Detailed location-specific studies, typically involving numerical wave models and local bathymetry/topography data but possibly using empirical formulae, are required to estimate localised wave set-up and run-up effects. These wave analyses are outside the scope of this report, but there are exposed locations along the Nelson coastline where wave attack should be considered in the setting of minimum ground and building-floor elevation requirements, e.g., Figure 4-4.

Monaco, inside Waimea Inlet and sheltered by Tahunanui Spit, is not expected to be affected by the occasionally large waves experienced on the open coast, but will instead experience relatively small waves generated by wind blowing over the harbour or residual waves that penetrate the Inlet around high tide and decay further as they refract around into Monaco. Appropriate values of wave set-up and run-up for Monaco can be estimated using empirical formulae. Assuming a 15 m/s wind speed blowing across a 3 km fetch at high tide with average water depth of 5 m, the TMA shallow-water wind spectrum (Bouws et al. 1985) predicts a significant wave height (crest to trough) of ~0.25 m and wave period ~2 s. Using these values plus a relatively steep (conservative) 1:10 estimate of the beach slope in the empirical equations of Stockdon et al. (2006) we get a wave set-up estimate of ~0.05 m and a wave run-up estimate of ~0.12 m, giving a combined set-up of ~0.17 m. Based on this analysis, the existing allowance of 0.2 m for wave set-up and run-up for Monaco in the current 2003 NCC Engineering Standard is sensible.

Figure 4-4: Aerial photograph of wave set-up and run-up at Rocks Road taken at ~13:00 during the 19 March 1957 storm. [*Supplied by M. McGuire, Port Nelson*].

5. Coastal climate-change and sea-level rise

The Intergovernmental Panel on Climate Change (IPCC) published their 4th Assessment Report (AR4) in 2007. The IPCC Working Group I report (IPCC, 2007) describes in detail the changes that have already taken place in regional and global climate and provide climate projections for the future. These projections are based around possible emission scenarios defined in the IPCC *Special Report of Emission Scenarios* (IPCC 2000)[11] and depend on how the global economy might track over the rest of this century with respect to a range of socio-economic factors including usage of fossil fuels, population and economic growth.

Relevant parts of IPCC 4th Assessment Report that relate to coastal areas along with and New Zealand-based observations have been incorporated in the 2nd Edition of the Ministry for the Environment (MfE) *Guidance Manual for Local Government on Coastal Hazards and Climate Change* (MfE 2008). MfE also published a summary of this Guidance Manual called *Preparing for Coastal Change* (MfE 2009) which also has some informative factsheets on storm surge and coastal inundation. Both are available from the MfE web page.[12]. This section draws on this material in deriving a range of possible sea-level rise values and possible increases in storm surge by the end of this century that are appropriate for Nelson City.

5.1 Planning framework

Coastal planning aspects of the revised Nelson Resource Management Plan (NRMP) being prepared by Nelson City Council on behalf of the community needs to give effect to the Resource Management Act or RMA (1991 and subsequent amendments), the operative NZ Coastal Policy Statement (currently the 1994 NZCPS) and any relevant National Policy Statement or National Environment Standard.

Under the RMA, in Part II, Section 7, all persons exercising functions and powers under the Act in relation to managing the use, development and protection of natural and physical resources, shall have particular regard to several other matters including subsection 7(i): the effects of climate change.

The Government are currently preparing a proposed National Environment Standard (NES) on sea-level rise and a revised 2009 NZ Coastal Policy Statement (NZCPS) is due out shortly (but not before this report is published). Both these statutory

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[11] http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/
[12] http://www.mfe.govt.nz/issues/climate/resources/local-govt/index.html

documents will have a bearing on the NRMP, as it will need to give effect to these instruments. However, the proposed NES may take up to 2 years before it becomes operative. As a starting position, the draft NES to go out for public consultation in August/September 2009, is likely to go with the sea-level rise guidance on p. 8 of *Preparing for Coastal Change* (MfE 2009) and p. 20–22 in the detailed Guidance Manual (MfE 2008). Consequently, the approach adopted in this report to selecting appropriate sea-level rise values, that are commensurate with the risk (what's at stake in terms of assets and indirect impacts) and the potential need for adaptation measures, will follow the current guidance recommendations.

Section 32 of the RMA 1991 imposes a duty on Councils to follow a defined process when preparing, or making changes to, a resource management plan. This process involves the consideration of various options and the appropriateness of any provisions intended for inclusion in the plan – how effective and how efficient they may or may not be. Before a change to a resource management plan is notified by a territorial local or regional authority, the authority must carry out an evaluation of the proposed change under Section 32 of the Act. The evaluation needs to consider the extent to which objectives, policies, rules or other methods are the most appropriate to achieve the purpose of the RMA, and also take into account benefits/costs and the risk of acting or not acting if there is uncertain or insufficient information. This report provides some of this information supporting a revision of the NRMP, with respect to the effects of climate change on planning associated with the built environment around the coastal environment of Nelson.

5.2 Planning timeframes

Sea-level rise is a progressive or "creeping" upwards trend that is affecting daily through to extreme sea levels around most of the world's coasts.[13] Up until the end of last century, the rate of sea-level rise has been relatively slow. This meant that planning and engineering design rightly focused on extremes due to climate variability. For example, designing for an average recurrence interval (ARI) event of 50 or 100 years, for parameters such as water level, flood levels or rainfall which remained stationary (i.e., no trend) with time as shown by the annual mean sea-level example in top panel in Figure 5-1. However as the rise in sea level continues to accelerate, there is an increasing imperative to consider the effects of climate variability on top of a rising trend when planning for future development. This upwards trend also means the definition of realistic (rather than nominal) planning

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[13] Some parts of the world have negative trends in relative sea-level rise due to the uplift of the land mass from crustal rebound following the last Ice Age e.g., parts of Scandinavia

timeframes becomes much more important than it was in the past, as shown by the example in Figure 5-1.

It was agreed at a joint NCC-NIWA workshop (2 July 2009) that the revised NRMP should cover a planning time frame out to 2100 with respect to coastal inundation (but also provide examples of interim levels for perhaps 2050 for illustrative purposes).

Note: planning or designing for a 100-year ARI event is not the same as a 100 year planning timeframe, especially in the context of a rising trend.

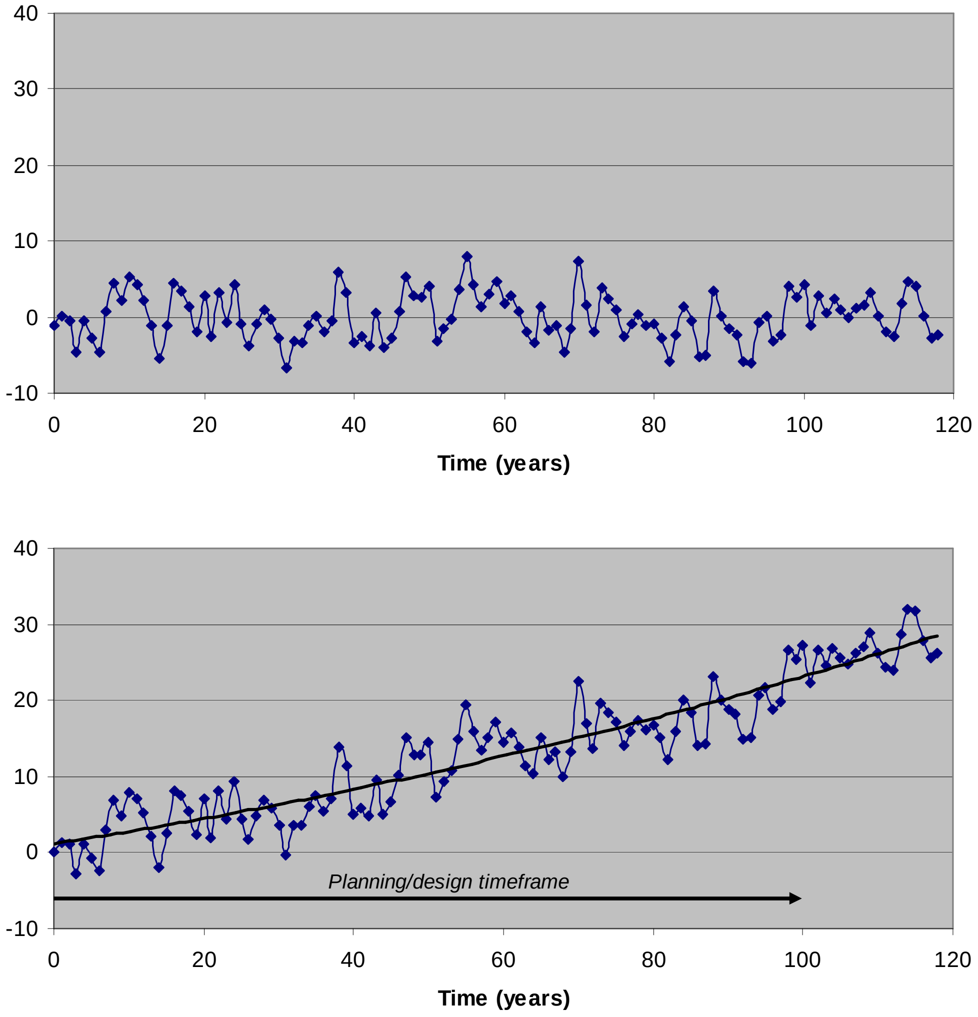

Figure 5-1: Example of: (TOP) a stationary time series with no long-term trend, compared with (BOTTOM) the same time series on the back of a rising trend, illustrating the importance of selecting an appropriate planning/design timeframe as well as an ARI extreme level.

5.3 Historic and recent sea-level rise

Sea-level rise (SLR) was relatively slow in New Zealand from 1500s to late 1800s at an estimated rise of 0.3±0.3 mm/yr (Gehrels et al. 2008). Over the past century (1900–2000), sea level rose at a higher rate, with an average relative SLR of 1.6±0.2 mm/yr across New Zealand's four main ports (Hannah 2004), which is an average rise of 0.16 m in that time period. An updated analysis to the present (2008) shows the four-port average SLR is now at 1.67 mm/yr (J. Hannah *pers. comm.*) The record at the Port of Nelson is too short (data only available since 1984) to extract sea-level trends locally. The nearest main port to Nelson is Wellington which has exhibited a relative SLR of 2.0±0.17 mm/yr up to 2008 (J. Hannah *pers. comm.*). The port SLR values are relative to the landmass on which the tide gauge is mounted, so in the Wellington case the higher value (compared to the average) could be explained by local or regional subsidence or tilting offsetting post-glacial rebound—but this will be clarified by a research project starting next year.

Adding an estimated 0.5 mm/yr for crustal rebound in the NZ region (Hannah 2004) to the average relative SLR for NZ of 1.6 mm/yr last century means an estimate of the absolute (eustatic) SLR in NZ is around 2.1 mm/yr. This is within the range of 1.7±0.5 mm/yr for the global average absolute SLR last century (IPCC 2007) and confirmed by the mean annual sea level from New Zealand's longest running tide gauge at Auckland (shown later in Figure 5-4).

A recent increase in the rate of sea-level rise has been observed by satellite altimeters (Figure 5-2). The current rate of rise of global mean sea level (GMSL) computed from these satellite data (January 1993 to May 2009) is 3.3 ± 0.4 mm/year and that rate has been more-or-less steady over that period.[14] This is more than 50% larger than the global average value over the 20th century (Figure 5-2). The global average rate of rise derived from long-term tide gauge records has also recently increased to catch up with the earlier acceleration shown by the satellite record (Figure 5-2). Whether or not this represents a further increase in the rate of global SLR or also has a contribution from long-period climate variability is not yet certain.

Satellites such as TOPEX/Poseidon, Jason-1 and Jason-2 have also provided new insight into the complex geographical patterns of sea-level change. The New Zealand region is responding at around or slightly above the satellite-derived mean SLR[14] again confirming that sea-levels in the New Zealand area are responding at close to global average rates.

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[14] CSIRO: http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html

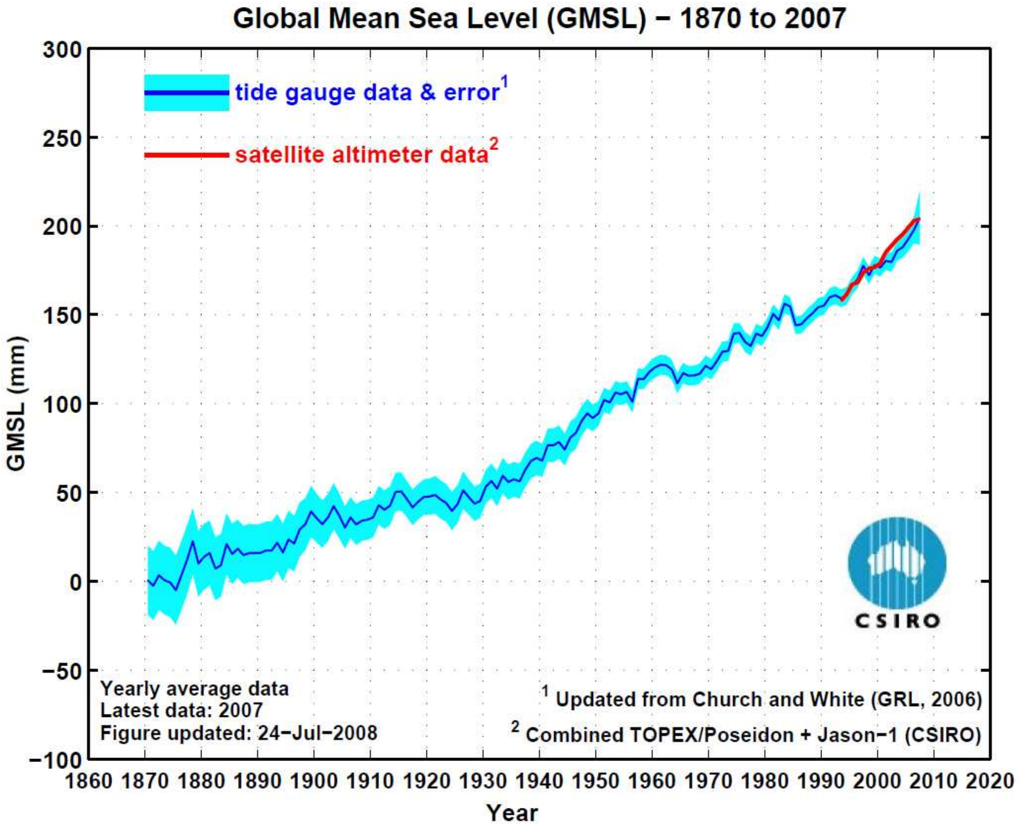

Figure 5-2: Global mean sea level from a network of long-term tide gauges (updated from Church & White (2006) compared to recent measurements from satellite altimeters from 1993 to 2007. [*Source:* CSIRO Marine & Atmospheric Research].

5.4 Causes of sea-level rise

Long-term changes or trends in relative sea level in a particular ocean region are typically due to a combination of three main components:

1) Global average eustatic or absolute sea-level rise. This is due to a combination of:

- an increase in ocean volume due to lower density arising from warmer ocean temperature and lower salinity causing an increase in ocean volume; and

- an increase in ocean mass due to a re-distribution in the exchange of fresh water between land-based storage (for example, glaciers, ice sheets, dams, lakes, rivers and groundwater) to the oceans;

Thermal expansion (the 1st factor) is expected to contribute more than half of the average SLR, but land-based ice will lose mass at an increasing rate as the century progresses.

2) Departures (positive or negative) from the global average in different sub-regions of the world's oceans, which in New Zealand's case is the South West Pacific. Examples are differences due to non-uniform patterns of temperature and salinity change, variations in mean surface atmospheric pressure and wind stress, and varying response of ocean current circulation to climate change. As yet these geographical variations are poorly understood and can be significant.

3) Local vertical land movements. The landmass can either be stable, subsiding or rising. The latter two can be either incremental tectonic shifts for example as the result of an earthquake, or gradual due to crustal loading of sediments or re-bound of the crust following the last Ice Age.

It is important to note that IPCC only provides projections for the first component (global mean) and some general guidance on the second component. At the local level, it is the relative SLR, as measured directly by a local tide gauge, that is important for planning and design for land-based activities and development.

5.5 Projected sea-level rise by 2100

In terms of past IPCC projections (in the 1st to 3rd Assessment Reports completed in 1990, 1995 and 2001 respectively), the global mean sea level has so far been tracking at the higher end of the projected ranges. Figure 5–3 shows an example comparison with the 3rd Assessment Report (2001) projections, which had an upper bound SLR of 0.88 m by 2100 (relative to 1990), and recent global-averaged measurements from the tide gauges and satellite altimetry. Overall, these observational data underscore the concerns about global climate change. Previous projections, as summarized by IPCC, have not exaggerated but may in some respects even have underestimated the change for sea level (Rahmstorf et al. 2007).

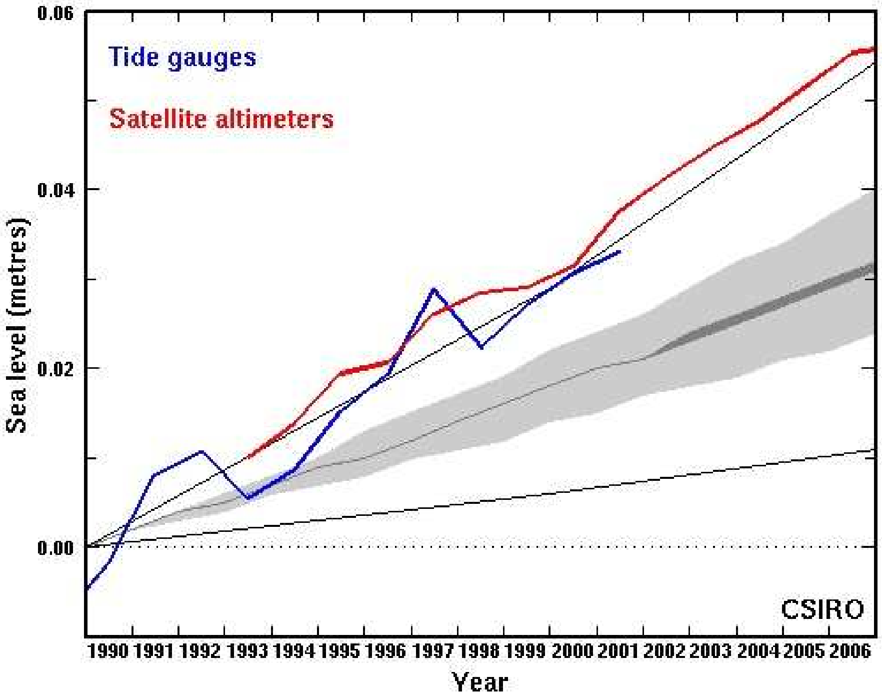

Figure 5-3: Recent observations show the observed sea levels from tide gauges (blue) and satellites (red) are tracking near the upper bound (black line) of the IPCC 2001 projections (grey shading and black lines) since the start of the projections in 1990 [Source: Rahmstorf et al. (2007) and CSIRO Marine & Atmospheric Research].

As SLR in New Zealand is tracking close to the global average SLR, as shown in Section 5.3, it is reasonable that the IPCC projections can be applied directly to the NZ situation. Research in progress in New Zealand over the next 3–5 years on the second and third components of SLR (previous section) will be able to provide more definitive results of vertical landmass movement and the New Zealand-wide departures from the global average sea level to improve the downscaling of future IPCC projections on SLR. The overlay of relative sea-levels from the Port of Auckland on the historic global SLR in Figure 5-4 shows that there is a close link with the global average and these other components are likely to be secondary.

In the meantime, outputs from global climate models show the departure of SLR from the global average in the New Zealand region (IPCC 2007) is estimated to be a further 0.05 m above the global-mean SLR by the 2090s. This has been factored into the MfE guidance on sea-level rise (MfE 2008, 2009).

The basic range of projected sea-level rise estimated in the Fourth Assessment Report (IPCC 2007) is for a rise of 0.18 m to 0.59 m by the decade 2090–2099 (2090s) relative to the average sea level over the period 1980 to 1999 (Figure 5-4). This is based on projections from 17 different global climate models for six different future emission scenarios (IPCC 2000) shown by the bars on the right-hand side of Figure 5–4 for a 5 to 95% interval characterising the spread in model results.

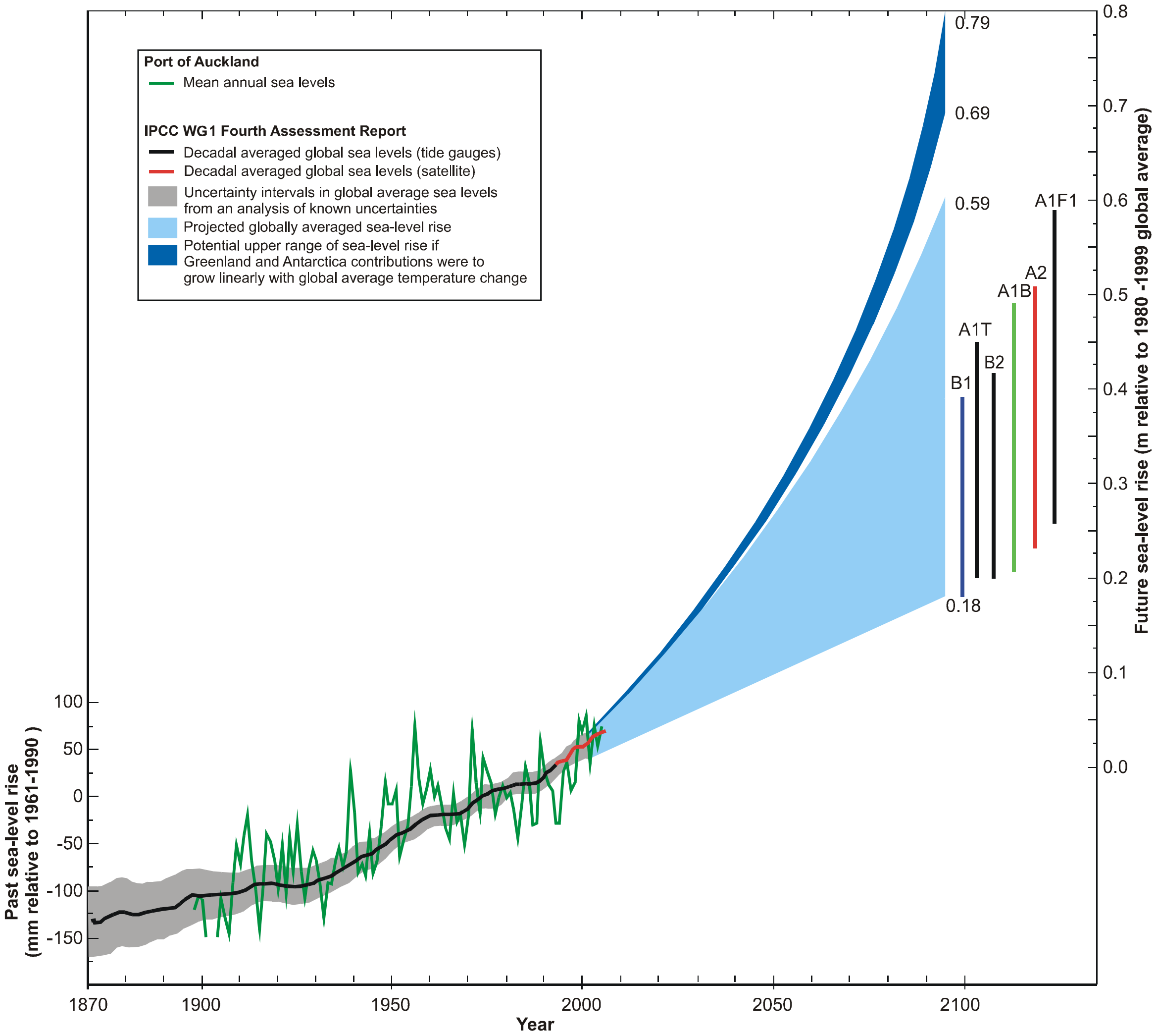

Figure 5-4: Global mean sea-level rise projections to the mid 2090s. The black line and grey shading on the left hand side show the decadal averaged global sea levels and associated uncertainty respectively, as measured by tide gauges throughout the world. The red line is the decadal averaged sea levels as measured by satellites since 1993. The green line is the mean annual relative sea level as measured at the Port of Auckland since 1899. The light blue shading shows the range in projected mean sea level out to the 2090s. The dark blue line shows the potential additional contribution from Greenland and Antarctica Ice Sheets if contributions to sea-level rise were to grow linearly with global average temperature change. The vertical colour lines on the right-hand side show the range in projections from the various global climate models for six emission scenarios from IPCC (2000).

However, these SLR projections (light blue shading in Figure 5–4) exclude uncertainties in carbon-cycle feedbacks and the possibility of faster than expected ice melt from Greenland and Antarctica ice sheets.

While the basic set of SLR projections do include sea-level contributions due to ice flow from Greenland and Antarctica remaining at the rates observed between 1993 to 2003, it is expected that these rates will increase in the future particularly if greenhouse gas emissions are not reduced. Consequently, an additional 0.1 to 0.2 m rise in the upper ranges of the emission scenario projections (dark blue shading in Figure 5-4) would be expected if these ice sheet contributions were to grow linearly with global temperature change.

An even larger contribution to SLR from these ice sheets, especially from Greenland, over this century cannot be ruled out. In its Fourth Assessment Report (IPCC 2007), the IPCC has found that "*Because understanding of some important effects driving sea-level rise is too limited, this report does not assess the likelihood, nor provide a best estimate or an upper bound for sea-level rise.*"

Since the cut-off period of peer-reviewed literature considered by IPCC (2007), there have been several scientific papers published on ice-sheet dynamics and mass budgets and the possible contribution to a range of possible higher SLR values by 2100. Some of these upper-bound estimates of SLR from recent papers (e.g., Rahmstorf 2007; Horton et al. 2008; Pfeffer et al. 2008) using semi-empirical techniques (e.g., using past correlations of air temperature increase and SLR) are shown in Figure 5-5 and compared to the projections from the 3rd and 4th IPCC Assessment Reports. Further detail on these recent studies is available in the MfE Guidance Manual (MfE 2007). A very recent paper (Siddall et al. 2009), using reconstructions of sea-level rise since the last Ice Age, show that a maximum SLR may reach 0.82 m by 2100 (which is closer to the IPCC 4th Assessment upper range SLR of 0.79 m by the 2090s). While based on semi-empirical approaches, these recent studies indicate that a rise of 1 m or more by 2100 cannot be ruled out. Much further work is now required on modelling ice-sheet dynamics and quantifying ice mass losses through observations to provide more definitive projections of upper-bound SLR in future IPCC Assessment Reports.

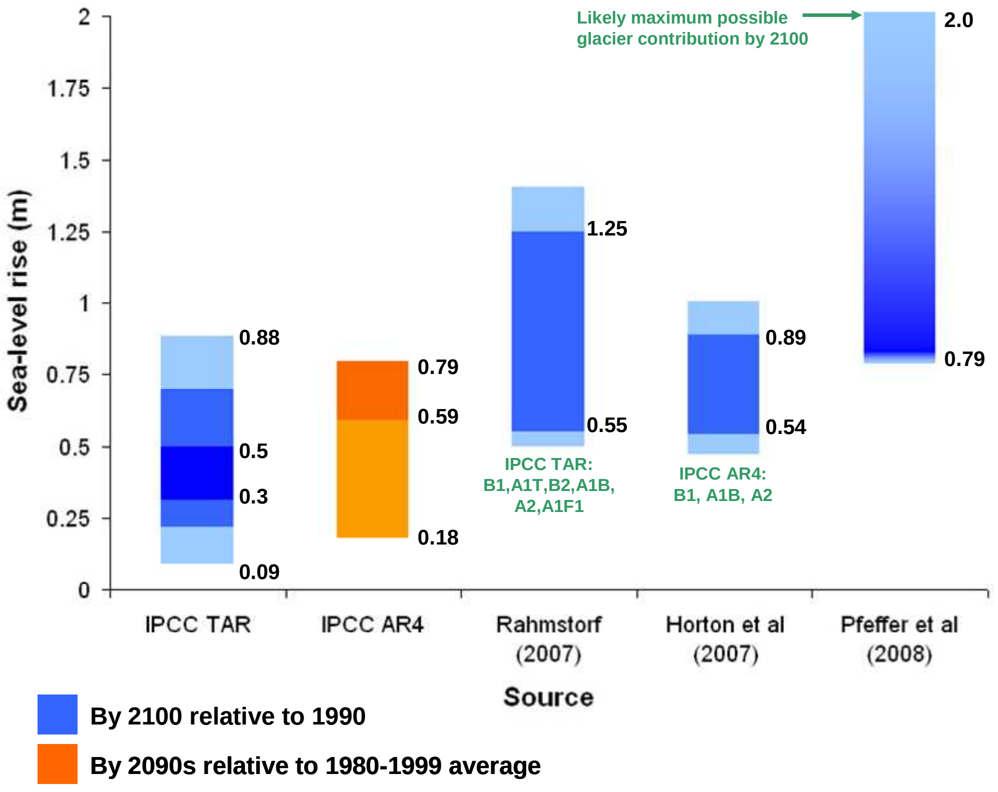

Figure 5-5: Ranges of global mean sea-level rise projections by 2100 (2090s in the case of the 4th Assessment Report or AR4) from the last two IPCC assessments (TAR=Third Assessment Report) and three recent papers published since the cut-off period considered by IPCC (2007). Rahmstorf (2007) used air temperature projections from climate models in TAR for 6 emission scenarios while Horton et al. (2008) used climate model results for 3 emission scenarios in AR4.

5.6 Projections for sea-level rise beyond this century

Sea-level will not stop rising at 2100.

Sea level is likely to continue rising for many centuries into the future, even if some stabilisation of emissions is achieved in the next few decades. This long lag response is due to the long lag times in the deep ocean’s heating response to climate warming from past emissions compounded by ongoing future emissions (MfE 2008).

IPCC (2007) discussed the commitment to climate change, including sea-level rise, already in place from emissions during the 21st century by extending 8 global climate model simulations for a scenario where emissions stabilise at greenhouse-gas concentrations of 700 ppm (CO_2–equivalents). The results show that emissions during the 21st century continue to have an impact even at year 3000 and beyond for sea-level rise due to thermal expansion only (ice-sheet mass contributions were not included). Figure 2.6 in MfE (2008) shows these results, ranging from a 0.6 m to 2.0 m SLR by 3000 AD (relative to 2000), but only for the thermal expansion component of SLR.

Stabilisation of future emissions will also play an important role in determining the potential contribution of the two major uncertainties associated with longer-term SLR, that of the Greenland and West Antarctic ice sheets. Catastrophic contributions to sea-level rise from collapse of the West Antarctic Ice Sheet or the rapid loss of the Greenland Ice Sheet are not considered likely to occur this century. However, the occurrence of such catastrophic changes becomes increasingly more likely in the next century as greenhouse gas concentrations continue to rise, and could contribute several metres to SLR (IPCC 2007; MfE 2008).

5.7 Guidance on selecting appropriate SLR values

Given that New Zealand-wide sea levels are rising at similar rates to the global average rate, and reviewing both the IPCC (2007) projections and upper-bounds from recent studies, the MfE Guidance Manual and Summary (MfE 2008, 2009) recommends the following SLR values for New Zealand locations based on a risk assessment basis.

For planning and decision timeframes out to the **2090s** (2090–2099):

1. a base value sea-level rise of 0.5 m relative to the 1980–1999 average be used, *along with*;

2. an assessment of potential consequences from a range of possible higher sea-level rise values. At the very least, all assessments should consider the consequences of a mean sea-level rise *of at least 0.8 m* relative to the 1980–1999 average.

For planning and decision timeframes **beyond 2100**:

For longer planning and decision timeframes beyond the end of this century, we recommend an additional allowance for sea-level rise of 10 mm per year beyond 2100.

As demonstrated, there are uncertainties associated with sea-level rise and especially the upper bound by the end of this century. Nevertheless, local government must continue to make decisions that either implicitly or explicitly make assumptions about what this sea-level rise will be over the lifetime of a particular development, community assets or infrastructure.

Risk management is a prudent and pragmatic approach for incorporating uncertainties such as those associated with future sea-level rise. Using a risk management approach involves broad consideration of the potential impacts or consequences of sea-level rise on a specific decision or issue.

Any decision on the extent of sea-level rise to plan for, should consider (MfE, 2009):

- the possibility and consequences of particular sea levels being reached within the planning timeframe or design life [to 2100 in case of the NRMP];
- the potential costs that could be incurred in future adapting to a particular sea-level rise;
- how any residual risks would be managed for consequences over and above a particular sea-level rise threshold, or if the sea-level rise that is planned for is underestimated.

Potential consequences for coastal inundation from storm-tide events riding on the back of various SLR values were assessed during a NCC/NIWA workshop (2 July, 2009). The basis for the qualitative risk assessment of consequences were a series of preliminary inundation maps prepared by NCC of the Nelson city area for a storm-tide event reaching 15.0 m (NCC Datum) and various SLR values of 0.3, 0.5, 0.8, 1.0, 1.2 m by 2100. These inundation overlays were derived in the NCC GIS system draping the various static water levels over the NCC digital elevation model generated from a LiDAR survey.

Factors considered at the workshop in selecting appropriate SLR values included:

- GIS inundation overlays showed that the additional area of the city that could be inundated by a severe storm-tide diminished rapidly above SLR of 0.8 m i.e., there would only be a marginal increase areas affected by high SLR due to the rising and hilly topography on the margins of the very flat areas.

- The lower areas of the city such as the northern end of the Nelson CBD are already occasionally affected by high storm-tide levels so any further SLR would continue to exacerbate the consequences. For low-lying areas, an assessment of 0.8 m SLR by 2100 should be a minimum and depending on the risk profile of the development, a 1 m SLR by 2100 may need to be considered (e.g., high-value infrastructure).

- The MfE (2008, 2009) guidance recommends at the very least to consider a base value of 0.5 m SLR by 2090–99 and also assess the potential consequences of at least a 0.8 m SLR.

- The starting point for a proposed National Environment Standard (NES) on sea-level rise would be the recommendations in the MfE guidance material (see box on previous page).

- With respect to minimum ground level standards for Nelson City, pushing the SLR value too high may lead to adverse affects on drainage for adjoining properties. Therefore some consideration is also required to integrate the ground minimum levels with minimum floor levels and the style of building foundation e.g., raised pile and perimeter wall foundations compared to conventional poured floor slab construction to provide greater flexibility for future adaptation and reduced adaptation costs.

Consequently, SLR values of 0.5 m, 0.8 m and, for some situations of higher risk, 1 m SLR by 2100 were selected to be added to the storm-tide recommendations from Section 4 for minimum ground levels in coastal areas (excluding river flooding). The likely corresponding SLR values at the 2050 juncture are 0.23 m, 0.31 m and 0.37 m.

Note: the guidance relates to a baseline mean sea level for the period 1980–99. In Section 4, Port Nelson tide records from 1984 to early 2009 were used in the storm-tide analysis, thus including a small amount of SLR beyond 2000. However, taking into account that the MfE guidance on SLR is averaged for the period 2090–99 (2090s) rather than the slightly longer 2100 planning timeframe adopted in the Report, these would cancel out, so the recommended SLR values above can be added straight onto the storm-tide ARI levels from Section 4.

Beyond 2100, the guidance recommended by MfE (2008, 2009) of 10 mm per year should be used, recognising the uncertainty in SLR will increase with the number of years beyond 2100.

5.8 Climate-change effects on storm surge

Changes in storm surge (produced by low barometric pressures and adverse winds) will depend on changes in the frequency, intensity and/or tracking of low-pressure systems, and occurrence of stronger winds associated with these systems. Changes, particularly in intensity of storms, are likely to occur, but the frequency of severe storms may not change significantly (MfE, 2008, 2009). Much less certain are how these changes in storms may translate into changes in the magnitude or frequency of storm surges in New Zealand.

Due to uncertainties over changes to storms in central New Zealand by 2100, no additional factor is applied for the effect of climate-change on storm surges (where winds and low-pressure storm intensities could be affected by changes in climate). Therefore, the storm-surge heights (and their associated ARI) estimated in Section 4 are assumed to apply through to 2100.

Climate modelling of New Zealand regions out to 2100 is underway by NIWA over the next few years, which should provide more definitive projections on changes to winds and storms. An allied 3-year NIWA research programme *Waves and Storm-surge Projections* (funded by the NZ Foundation of Research, Science & Technology) has commenced with a specific goal of translating potential changes in winds and storm intensities into what changes may occur for storm surges and wave climate at a regional level.

5.9 Climate change effects on tide exceedances

On the open coast of Tasman Bay and probably Port Nelson, sea-level rise won’t significantly alter the tide range. However, up in Waimea Inlet, the tide range may change somewhat, depending on the net effect of sediment deposition on the seabed versus sea-level rise. What will change substantially as sea-level rise accelerates are the occurrences when high tides exceed a specific elevation.

This is shown in Figure 5-6, where the high–tide exceedance curve for the existing situation at Port Nelson (similar to Figure 3-4 but in NCC Datum) is compared with two other high-tide exceedance curves for sea-level rises of 0.5 m and 0.8 m. The comparison shows that the present perigean-spring high tide (“king tide”) elevation is exceeded by only 5% of all high tides currently, but with sea-level rises of 0.5 m and 0.8 m, this same elevation is exceeded by 40% and 66% of all high tides respectively. Therefore as sea-level rise increases, the incidence of higher high-tides exceeding shoreline crest elevations will increase substantially as the tide rides on the back of the elevated sea level.

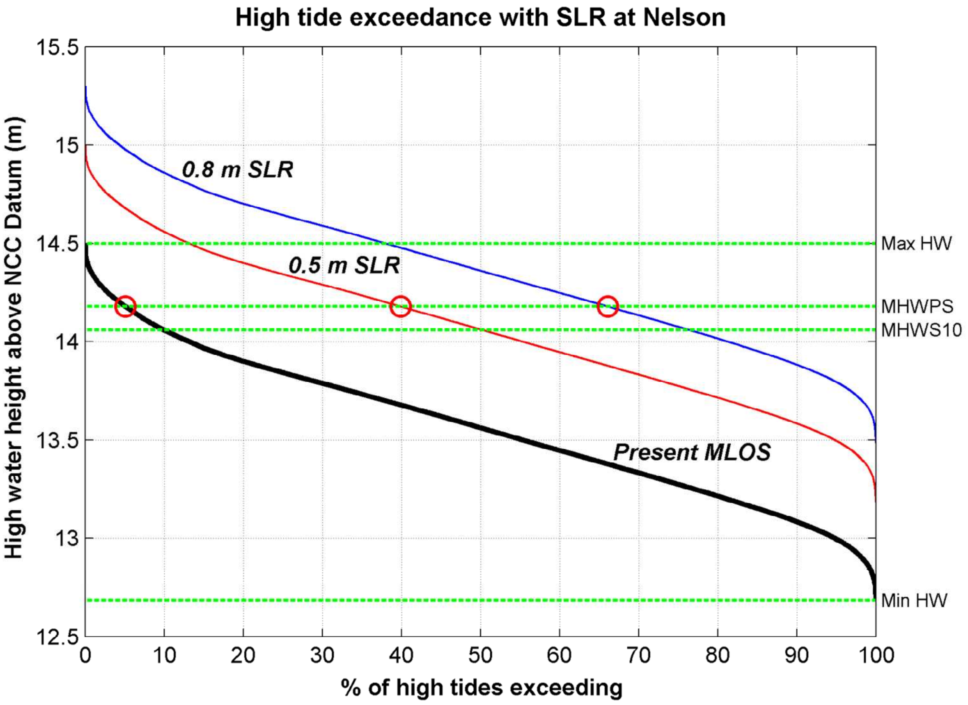

Figure 5-6: High tide exceedance at Nelson relative to NCC Datum for the present mean level of the sea (bottom curve) compared with the exceedance curves for sea-level rises of 0.5 m and 0.8 m (top two lines respectively). The percentage of high tides that exceed the present perigean-spring ("king") tide elevation of 14.18 m NCC Datum is 5%, but with a sea-level rises of 0.5 m and 0.8 m, this same elevation would be exceeded by 40% and 66% of all high tides.

5.10 Climate change effects on storm-tide exceedances relative to minimum ground levels

Due to uncertainties over changes to storms in central New Zealand by 2100, no additional factor is applied for the effect of climate-change on storm surges. Since tidal characteristics on the open coast are also expected to remain largely unchanged by future sea level rise, storm tide characteristics are expected to remain similar. Therefore, to predict future extreme storm tides, sea level rise is simply added to the present-day storm tide analysis from Section 4.

However, sea-level rise causes an upward translation of the extreme storm-tide exceedance curve, as shown in Figure 5-7 (similar to that for the high-tide exceedance curves). For present-day MLOS, there is a 0.5% (0.005 AEP) chance of a storm tide that equals or exceeds 15.0 m RL. The purple dashed line shows that if 0.3 m sea level rise occurs (and storm surge characteristics don't change), then the probability of the same storm tide elevation being reached or exceeded in any given year increases from

0.5% to 36% (0.36 AEP or ARI of 2.7 years). For larger sea level rise of 0.5 or 0.8 m, the 15 m elevation is expected to be exceeded at least once every year. Therefore as sea-level rise increases, the incidence of higher storm tides exceeding shoreline crest elevations will increase substantially as the storm tide rides on the back of the elevated sea level. Therefore minimum ground levels would have to keep pace with sea-level rise to maintain the same annual exceedance probabilities as exist for the present mean level of the sea.

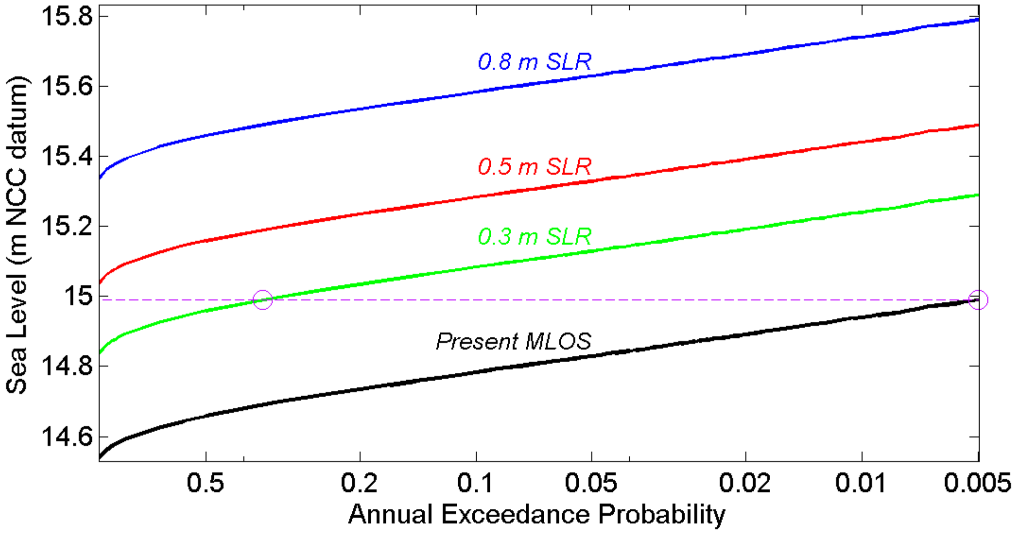

Figure 5-7: Extreme-value storm-tide curve for present MLOS (including +0.1 m for uncertainty in MLOS), with vertical translations for sea-level rise values of 0.3, 0.5 and 0.8 m. As an example, for present-day MLOS, there is a 0.5% (0.005 AEP) chance of a storm tide that equals or exceeds 15.0 m RL. The purple dashed line shows that if 0.3 m sea level rise occurs, then the probability of the same storm-tide elevation being reached or exceeded in any given year increases from 0.5% to 36% (0.36 AEP or ARI of 2.7 years). For higher sea-level rises of 0.5 or 0.8 m, the 15 m RL elevation is expected to be exceeded at least once every year.

A similar plot can be used to evaluate what the residual risk to inundation exposure would be by 2100 for previously-developed properties that have used minimum ground levels from the current 2003 Nelson City Council Engineering Standards (which factored in an allowance for a 0.3 m sea level rise by 2050). If a 0.8 m sea-level rise occurs by 2100, then an additional sea-level rise of 0.5 m will not have been factored into minimum ground levels of these past developments. Figure 5-8 shows that if sea level rise of 0.3 m occurred by 2050, then the current design sea level of 15.3 m (Table 4-1) has a low 0.5% (0.005 AEP) probability of occurring in any given year, as it is presently (because the 0.3 m rise has been built into the ground level requirements). However, if sea level reaches 0.8 m above present by 2100, then storm tides exceeding the 15.3 m design ground level will become much more frequent, occurring on average at least once every year. If sea-level rise only reaches 0.5 m by 2100 (i.e., an additional 0.2 m above the 0.3 m allowed for), then storm tides exceeding the 15.3 m design ground level would occur on average once every 10 years (0.1 AEP) compared to once on average every 200 years presently.

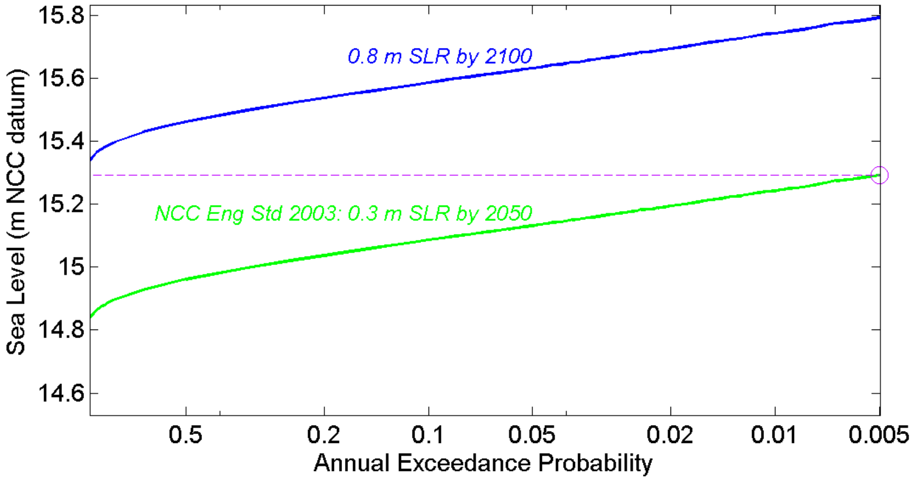

Figure 5-8: Extreme-value curve including 0.3 m sea level rise by 2050 as currently included in the NCC Engineering Standards 2003, compared with that for sea-level rise 0.8 m by 2100. An additional 0.5 m sea-level rise would translate to a situation of at least once per year exceedance of the 15.3 m elevation in 2100.

6. Recommendations for minimum ground level requirements

6.1 Sheltered coastal and estuarine areas

Based on the calculations and reasoning discussed in Section 4 (storm-tide levels) and Section 5 (climate-change projections), the following Table 6-1 lists the recommended components that make up a minimum ground level in sheltered coastal and estuarine areas of Nelson City. This would apply to all parts of the Nelson coastal environment (landward of the coastal marine area) except those more exposed coastal areas specifically mentioned in Section 6.2.

The appropriate sea-level rise to include in the minimum ground level requirements has been determined based on both the risk exposure (i.e., high value assets require a higher precautionary sea-level rise) and limiting the potential effects on adjacent properties in existing developed areas e.g., drainage, aesthetics of uneven ground from fill material.

The following worked example illustrates the use of the procedure in Table 6-1 to arrive at a minimum ground level for a major infrastructure asset. The table shows the calculation of the minimum ground requirement of a high-value major infrastructure item with a planning timeframe out to 2100. The steps follow the procedure outlined in Table 6-1:

1. We will work to a 0.5% AEP (200-year ARI) since this is a major infrastructure development.

2–3. The “best estimate” (median) storm-tide (from Table 6-2, or Table 4-1) corresponding with 0.5% AEP is 5.06 m relative to Chart Datum (CD). But, because this is a major infrastructure development we will choose the maximum value corresponding with this AEP, which is 5.13 m CD.

4. Add 0.1 m to account for additional variability in MLOS that was not accounted for in the extreme-value analysis (Section 4): 5.13 m + 0.1 = 5.23 m CD.

5. Convert from Chart Datum to NCC Datum: 5.23 +9.83 m = 15.06 m NCC Datum.

6–7. A sea-level rise of 1.0 m by 2100 is appropriate, since this is a major infrastructure asset: 15.06 + 1.0 m = 16.06 m NCC Datum.

8–9. Waves are not relevant to this site.

Table 6-1: The process and recommended components used to derive a minimum ground level in sheltered coastal and estuarine areas of Nelson City for different risk profiles.

Storm tide	Sea-level rise	Wave set-up & run-up
1. Decide on appropriate AEP. 2. Find storm-tide level that matches chosen AEP from Table 6-2. 3. Generally, use the median value in Table 6-2 ("best estimate"), but for a high-risk scenario, the maximum estimate may be appropriate. 4. Add 0.1 m to allow for extra MLOS variability. 5. Convert from Chart Datum to NCC datum if required, using Figure 2-1.	6. Decide on sea-level rise scenario for planning timeframe to 2100. 7. Select from • 0.5 m, • 0.8 m, or • 1.0 m depending on risk assessment of exposed assets & future costs of adapting to climate change e.g., 0.5 m for toilet blocks and recreational assets –or- individual residential buildings within existing developed areas (e.g., infill housing or re-developed properties) where drainage or uneven ground may adversely affect neighbouring properties; 0.8 m for residential and commercial buildings in redeveloped blocks; 1.0 m for high-value infrastructure (excl. streets, which are essential for drainage) -or- new sub-divisions.	8. Monaco – add 0.2 m. 9. Glenhaven to Glenduan area, Delaware Bay, Tahunanui Spit and exposed and low-lying parts of properties fronting Rocks Road – add wave height factor based on site-specific wave run-up and set-up assessments by a recognised coastal practitioner (otherwise outside the scope of this report).

Table 6-2: Extreme storm-tide estimates for Nelson, reproduced from Table 4-1. The estimates are given in metres relative to Chart Datum, for present-day MLOS.

AEP	**0.5 (50%)**	**0.2 (20%)**	**0.1 (10%)**	**0.05 (5%)**	**0.02 (2%)**	**0.01 (1%)**	**0.005 (0.5%)**
ARI	**2**	**5**	**10**	**20**	**50**	**100**	**200**
Minimum	4.72	4.80	4.84	4.89	4.94	4.96	5.01
5% c.i.	4.73	4.80	4.85	4.89	4.94	4.99	5.02
Median	**4.73**	**4.81**	**4.85**	**4.90**	**4.96**	**5.01**	**5.06**
95% c.i.	4.73	4.81	4.86	4.91	4.98	5.04	5.12
Maximum	4.73	4.81	4.86	4.91	4.99	5.07	5.13

Table 6-3 contains recommended minimum ground levels for various types of infrastructure. The base value in the table is the median 0.5% AEP storm tide of 5.06 m CD, or 14.89 m NCC Datum (Table 6-2), plus an extra 0.1 m for variability of the mean level of the sea. An appropriate sea-level rise component is then added depending on an assessment of future consequences and possible costs or effort that would be required in adapting to higher sea levels. Categories associated with the three sea-level rise values could be: a) 0.5 m sea-level rise for low-value assets such as toilet blocks, playground and recreational facilities and car parking areas or for individual properties in already developed low-lying areas where there maybe adverse drainage and aesthetic impacts on adjoining properties; b) 0.8 m for re-developed residential blocks and commercial properties, and c) 1.0 m for high-value infrastructure assets and new subdivisions that would have a high cost of adaptation when higher sea levels are reached. Note other than major highways, redevelopment of suburban streets and roads should not be raised too high as they form an integral part of the drainage network when floods or storm-tide inundation occurs (although flooded streets can restrict vehicle access).

An additional safety factor of 0.2 m to allow for wave run-up is recommended for development in the Monaco area. A wave set-up and run-up height would be required on top of the values in Table 6-3 for open-coast environments in Glenhaven, Glenduan, Delaware Bay, Tahunanui and the exposed stretch of Rocks Road, where some low-lying parts of properties could be inundated by wave overtopping (Figure 4-4). The run-up height should be determined by a competent coastal practitioner.

Table 6-3: Recommended minimum ground levels for development or infrastructure with different risk profiles (higher risk in darker gray shades). Sea levels are given relative to NCC Datum, with values in Chart Datum in parentheses.

Description	Sea level components (m)	Low-consequences (m)	Medium-consequences (m)	High-consequences (m)
0.5% AEP storm tide +0.1 m extra MLOS variability	15.0 (5.16)	15.0 (5.16)	15.0 (5.16)	15.0 (5.16)
Sea-level rise	*+0.5*	15.5 (5.66)		
	+0.8		15.8 (5.96)	
	+1.0			16.0 (6.16)
Monaco (incl. waves)	*+0.2*	15.7 (5.86)	16.0 (6.16)	16.2 (6.36)

Caveats:

Monaco Spit – no wave modelling was undertaken, but empirical formulae used in Section 4.2 indicated that a 0.2 m allowance for wave set-up and run-up is likely to be reasonable given the limited wind fetch across Waimea Inlet (also limited to high tide periods) and the wave sheltering provided by the Tahunanui Spit.

Upper Waimea Inlet coastal areas (SW Nelson City) – no information is available on whether the tide is amplified or diminished relative to the Port Nelson tidal range. If the tide proves to be amplified relative to Nelson, then the tide component may need to be increased when applied to this area.

6.2 Exposed open-coast areas

The four areas of Nelson City that are exposed to the open waters of Tasman Bay are:

- Delaware Bay including the Spit.
- Stretch of coast from Glenhaven to Glenduan to the east of the Boulder Bank.
- Exposed stretch of Rocks Road between Tahunanui Dr eastwards until it enters the shadow zone of waves from the north provided by Haulashore Island (e.g., see aerial photo during the 19 March 1957 storm, Figure 4-4).

- Tahunanui Reserve and Recreational Area (Tahunanui Spit).

Storm-tide values (based on the Port Nelson gauge) can reasonably be applied to these exposed areas (even Delaware Bay where tide range is slightly smaller than at Nelson).

However, no allowance has been incorporated in minimum ground levels for wave set-up and wave run-up, which could exceed 1 m in vertical height. Therefore it is recommended that application for consents in these areas that are likely to be impacted by wave run-up include a detailed analysis of wave run-up by a competent coastal practitioner. Note: any assessment of tsunami run-up heights would need to cover a greater area, as they can penetrate much further inland than wind or swell waves riding on the back of a storm-tide.

As an indication (until a wave modelling study is commissioned by NCC), the requirement for wave run-up assessments in these four areas should be limited to:

- low-lying areas of Delaware Bay, including all of the Spit and the hinterland that has ground elevations less than 16.5 m[15] NCC datum plus the appropriate SLR (e.g., final elevation of 17.3 m RL for 0.8 m SLR) and within 100 m of the MHWS shoreline;

- for the stretch of coast from Glenhaven to Glenduan, low-lying land that has ground elevations less than 16.5 m NCC datum plus the appropriate SLR and within 200 m of the MHWS shoreline (greater propensity for coastal flooding due to very low-lying land even though it is behind the Boulder Bank at mostly 16.5 to 17 m RL in height);

- low-lying parts of properties adjacent to the road in the exposed section of Rocks Road between Tahunanui Dr eastwards until it enters the shadow zone of waves from the north provided by Haulashore Island (e.g., see aerial photo during the 19 March 1957 storm, Figure 4-4);

- the entire Tahunanui Spit (Tahunanui Reserve and Recreational Area) through to where it connects with Rocks Road and to the north of (but not including) Beach Road.

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[15] 16.5 m allows for 1.5 m of wave runup and setup on top of a 0.5% AEP storm tide for present MLOS of 15 m, to which SLR has to be added.

7. Evaluation of the findings in relation to S32 matters and long-term planning

For the most part, the proposed changes to minimum ground levels do not break new ground. Rather, they amend existing provisions in the Nelson Resource Management Plan (NRMP) and the associated NCC Engineering Standards (2003) in order to update those provisions in the light of the latest climate-change projections and with the benefit of improved methodologies for estimating extreme storm-tide levels.

The recommended changes are consistent with s.7(i) of the RMA [*have particular regard to the effects of climate change*], guidance for local government promulgated by MfE, the proposed NZ Coastal Policy Statement, and a proposal for a National Environment Standard on sea-level rise. While the latter two planning documents are yet to be finalised, every effort has been made to adopt sea-level rise values that should be in line with the final versions (although subject to consultation and changes by government officials).

In effect, the future consequences in terms of costs, effectiveness and potential need for further adaptation (as sea-level continues to rise) would be far greater if the NRMP is left unchanged, than by revising those provisions. A prudent and somewhat precautionary approach to selecting an appropriate sea-level rise to use has been incorporated into the minimum ground levels that are commensurate with the future risks (i.e., consequences and adaptation costs) if sea levels were to reach higher levels than planned for by 2100, but offset by potential impacts of drainage on adjacent properties for infill-type developments. Sea-level rises above 1 m by 2100 cannot be ruled out, but at this stage 0.5 and 0.8 m sea-level rises have been adopted for most situations and a 1 m sea-level rise value suggested for high-value infrastructure assets and new subdivisions that could result in high consequences (direct and indirect) and/or adaptation costs if sea level was to exceed a lower sea-level rise such as 0.8 m by 2100.

Specifying minimum ground levels in the proposed plan change is the most appropriate way at this stage to limit future consequences of development from a combination of high storm-tide and sea-level rise, and thereby limit impacts on council and for property or business owners. However, raising minimum ground levels too high in already-developed areas (e.g., infill or re-developed properties) can affect neighbouring properties especially in terms of drainage and the aesthetics of uneven steps in ground topography or building heights. It may be more effective to use a combination of minimum ground levels, minimum building floor levels and building foundation requirements in order to provide the most sustainable solution, especially in existing developed areas. In the case of the latter, a reduced level of service could be tolerated with respect to infrequent inundation of property grounds by 2100, by limiting the height minimum ground levels need to be raised (e.g., not applying safety or freeboard factors to values in Table 6–3 and using the lower SLR value of 0.5 m), but building in future flexibility by adopting floor levels (that would meet the Building Code ARI standard for inundation by a specified year) in tandem with foundation construction techniques that allow the building to be temporarily or permanently detached from the foundations. Such construction techniques means the building can be further raised in the future or transported off site when the frequency of coastal inundation becomes unsustainable at or beyond 2100. Such a combination of requirements is a “low regrets” adaptation approach, which has some additional up-front cost in terms of foundation construction, but in the long term minimises potential costs of adaptation or abandonment for future owners and/or council.

However, while a combination of minimum ground levels, minimum building floor levels and building foundation requirements is an interim medium-term measure that can reduce the future risks for new or renovation works in already-developed areas, there will be a need to develop long-term strategic adaptation plans for each low-lying area with a legacy of historic development. Such areas will eventually face an increasing frequency of coastal inundation as sea-level rises, to the point where it either: a) becomes economically viable to build substantial coastal protection works or pumping systems, or b) it becomes unsustainable and managed retreat is required as an end point.

Figure 7–1 shows simplistically the three main ways communities can adapt to coastal inundation and rising sea levels. The first approach is “protection” or defence of low-lying suburbs by protection works such as rock revetments, stop banks or sea walls or could be combined with pump systems (top panel, Fig. 7–1). This approach substantially reduces the hazard exposure without any requirements for works on individual properties, but can lead to catastrophic consequences if the protection works are overtopped or breached. There are also environmental impacts to consider especially natural character and public access. The long-term sustainability of using protection measures also needs to be factored into decisions on how the community can adapt to climate change.

The second adaptation approach (middle panel, Fig 7–1) is one of accommodating climate-change impacts by making changes to the built or natural environment e.g., dune care and replenishment on sand spits, regulating building development and raising buildings. Revising minimum ground levels with each new version of the NRMP is part of accommodating the effects of climate change but as shown diagrammatically (middle panel, Fig 7–1), it can be applied more effectively in tandem with limits on building floor levels and style of foundations. As mentioned above, this is where a trade-off is needed between reducing the serviceability of the property grounds (due to occasional inundation) by minimising the height for ground treatment and limiting the inundation of buildings through restraints on floor levels.

Finally, the third general adaptation approach is to reduce the exposure by planning for a retreat from the hazard. In existing developed areas, such an approach is considered as a last resort, but a long-term proactive plan may be required in some low-lying areas of Nelson where continued habitation will eventually become unsustainable as sea level continues to rise well beyond 2100. However, for proposed sub-divisions, this can be built in at the start by imposing a higher sea-level rise component in minimum ground level requirements (e.g., Tables 6–1 and 6–3), thereby avoiding the hazard exposure within a prescribed planning timeframe.

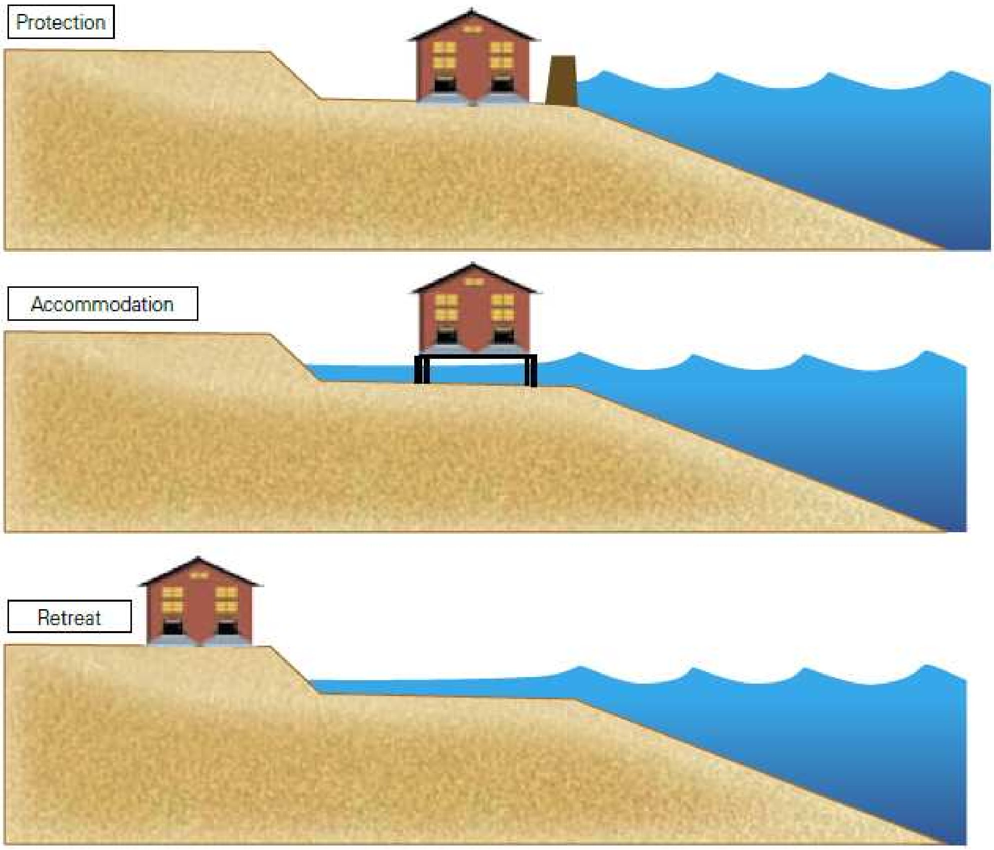

Figure 7–1: The three main approaches to adaptation in the coastal environment. [After Bijlsma et al. 1996].

In exposed low-lying coastal margins of Nelson City with a legacy of historic development, a staged combination of two or all three adaptation approaches for pre-defined future time periods may be required, along with an assessment of the exposure to river flooding and stormwater flash flooding from intense rainfall. It is beyond the scope of this report or NIWA to provide any further details or recommendations on such long-term strategic planning for Nelson City.

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9. Glossary

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

Average recurrence interval (ARI) – a given (high) sea level would be expected to be equalled or exceeded in elevation, once, on average, every "ARI" years. ARI = 1 / AEP.

Inverse barometer (IB) – change in sea level elevation due to changes in atmospheric pressure. The relationship is "inverse" because as the pressure decreases ("barometer" drops), the sea level rises.

Intergovernmental Panel of Climate Change (IPCC) – the leading body for the assessment of climate change, established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences. IPCC doesn't undertake any new research work but Working Groups assess already-published peer-reviewed literature.

Mean-level-of-the-sea (MLOS) – describes the variation of the non-tidal sea level on longer time scales ranging from a monthly basis to decades due to such things as sea temperature and variability in El Niño–Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO) patterns.

Relative sea-level rise – the net rise in sea level in a region due to climate change taking into account the vertical movement of the landmass and is the sea-level rise that should be planned for in that region. Because tide gauges sit on the landmass, they automatically measure relative sea-level rise. In New Zealand, vertical landmass movements due to rebound following the last Ice Age are relatively small, so until definitive assessments from continuous GPS are analysed over at least 10 years and a better estimate of regional sea-level rise in the SW Pacific, we should use the global-average projections from IPCC.

Risk – the chance of something happening that will have an impact on objectives. It is measured in terms of a combination of the probability (or frequency) of an event and its consequences. [*Source:* AS/NZS 4360 Standard on Risk Management].

Storm surge – change of sea level due to weather-related processes such as wind set-up and inverse barometer.

Storm tide – peak sea level resulting from the combination of the astronomical tide plus storm surge, plus the mean-level-of-the-sea. The storm tide reaches its peak at or near the time of high tide. The name “storm tide” reflects the role of the astronomical tide and the storm surge, which are generally the largest components.

Wind set-up – the “piling up” of water against the coast by an onshore (or alongshore) prevailing wind.

10. Appendix 2 – the empirical simulation technique

The empirical simulation technique (Goring et al. submitted) involves generating for each year a contribution from each of the four sea-level components: tide, tidal residual, storm surge and MLOS. These contributions are then combined and the maximum sea level for the year is found. This process is repeated many thousands of times to generate a sequence of annual maxima which can then be processed as if they were from a long series of "measured" data.

Each component is treated in a different way as follows:

10.1 Tide

The tidal constituents were used to forecast 20 years of high tides. There are 706 high tides each year, so starting from a random time, 706 high tides are drawn from the forecast sequence.

10.2 Tidal Residual

The cumulative distribution function (CDF) for the tidal residual at high tide was calculated from the 33 years of data. For each year of simulation, 706 values of tidal residual are drawn from the CDF using non-parametric bootstrapping. This involves generating 706 uniformly distributed numbers between 0 and 1, and finding the corresponding tidal residual from the CDF.

10.3 Storm Surge

The CDF for mean storm surge over 12.42 h intervals was calculated. For simulation, 706 values for each year are extracted using non-parametric bootstrapping.

10.4 MLOS

A residual MLOS is obtained by first subtracting the annual cycle. Any linear trend that might relate to sea-level rise for example, is removed first, then the CDF calculated. For simulation, monthly values for MLOS are extracted from the CDF using non-parametric bootstrapping.

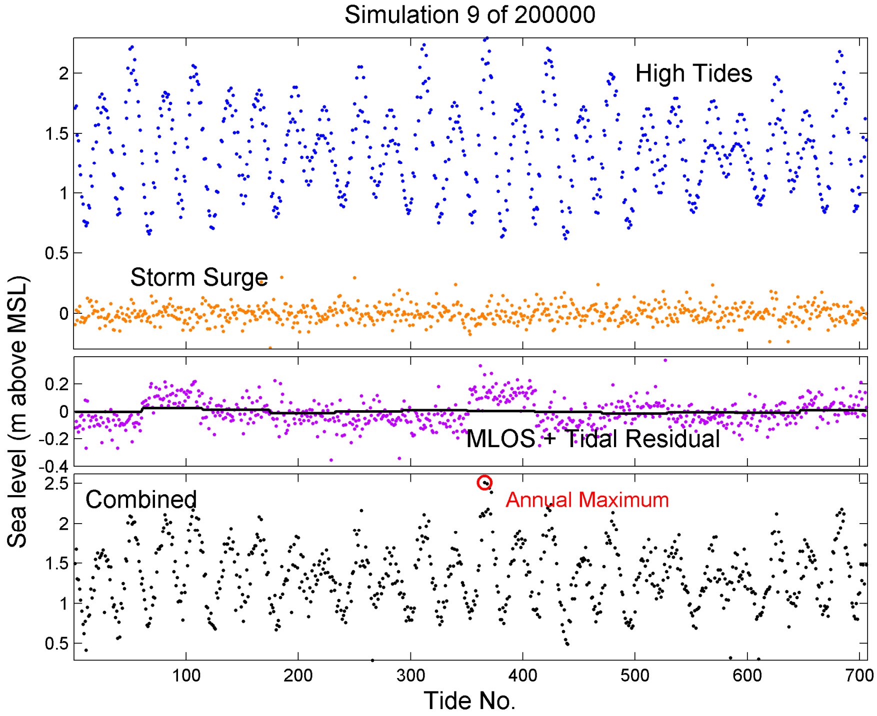

Figure 10-1: Typical year of simulation showing A. 706 high tides and the corresponding storm surge; B. residual MLOS + tidal residual (dots) and annual cycle (black curve); and C. total sea level with Annual Maximum marked.