Impacts of Climate Change on Urban Infrastructure & the Built Environment

A Toolbox

Toolbox 2.2.2: Causes of sea level variability

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Contents

1.	Causes of sea level variation	1
1.1	Wave-induced sea-level variability	1
1.1.1	Short waves	2
1.1.2	Long waves	2
1.2	Climate-induced sea-level variability and change	4
1.3	Unravelling sea-level variability	6
2.	Tidal harmonic analysis and New Zealand tides	10
2.1	Definition of mean high water springs	10
2.2	Red Alert days for coastal flooding	13
3.	Glossary	13
4.	References	15

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1. Causes of sea level variation

The height of the sea surface at the coast is constantly changing due to waves, tides and longer-term variations induced by weather and climate cycles. These 'drivers' of sea-level variability operate at various time scales, from a few seconds for wind waves up to century-scale climate change effects (Table 1.1). They fall into three categories: short waves (that break at the coast), long waves (that surge or inundate at the coast) and climate cycles and trends (more slowly varying changes in mean sea level driven by variations in climate).

Table 1.1: Listing of the main components and causes of sea-level variability at various timescales longer than 1 second, some of which overlap. Note: IFG=infragravity waves; ENSO=El Niño–Southern Oscillation; IPO= Inter-decadal Pacific Oscillation.

Phenomenon	Cause	Period
Short waves		
wind waves	winds	1 – 8 sec
swell	remote winds	8 – 25 sec
Long waves		
IFG waves (groups)	remote winds and surf beat	25 – 120 sec
far IFG, meteorological tsunami	moving weather systems	2 – 20 min
tsunami	earthquakes/landslides	5 min – 1 hr
seiche	resonance and weather	20 min – 4 hr
tides	astronomical	3 – 25 hr
storm surge	weather (winds and low pressure)	12 hr – 5 days
Climate cycles and trends		
annual (seasonal)	seasonal temperature cycle	1 yr
interannual	ENSO climate cycle	2 – 5 yr
inter-decadal	IPO climate cycle	20 – 30 yr
sea-level rise	climate change, crustal adjustments	> 50 yr

1.1 Wave-induced sea-level variability

If the word 'waves' is taken to mean 'vertical motions of the ocean surface', then *wind waves, swell, infragravity waves, seiches, tsunamis, tides* and *storm surge* are all 'wave' forms that contribute to sea-level variability. Waves are basically disturbances of the equilibrium state in any given body of material, which propagate through that body over distances and times much larger than the characteristic wave lengths and periods of the disturbances (Holthuijsen 2007). Usually when people think of 'waves'

at the sea they are thinking of wind-driven surface gravity waves, because they are easily observable over short periods of a few seconds.

1.1.1 Short waves

As the wind blows across the water, it transfers energy to the water surface, creating 'wind-driven surface gravity waves', so called because they are generated by the wind and gravity strongly influences their form (as opposed to water surface tension). Initially, tiny capillary 'ripples' form on the water surface (capillary wave form is influenced by water surface tension), but energy transfer continues to increase with the wind strength, duration and fetch (distance), turning ripples into wind-sea waves in the generation zone, which can then propagate away from the wind-generation zone as swell waves. *Wind-driven surface gravity waves* are characterised by their period of 1–25 seconds, with a wind sea comprising shorter period waves generated locally by winds and longer swell, generated by remote storms, sometimes from the other side of the Pacific Ocean.

1.1.2 Long waves

The first class of long waves are *infragravity waves* generated by groups or sets of wind waves or swell. They show up as a set of one or two higher waves that surge further up the beach before waning over periods of typically 25 seconds to a couple of minutes.

Similar, but longer period waves, can be generated by remote storm systems and propagate to the coast over periods of hours to a day or so with periods of 5 to 15 minutes. Swell waves travel in groups, and *far-infragravity* waves result from the water level set-down under groups of swell waves, having troughs that are beneath the larger waves of the group and crests in-between the wave groups. Similar tsunami-like waves can be generated by moving low-pressure storm systems or abrupt barometric pressure changes, known as *meteorological tsunami* or in the Mediterranean as *rissaga*. These long waves manifest as strong surging on a beach over several minutes or strong surging currents in ports that can sever ship moorings.

Seiches define slosh motions at a resonant frequency of a harbour, bay, or wider bight (e.g. Canterbury Bight). Seiches are generated by energy transfer from other processes, such as a regional wind field over a bay, infragravity waves at a harbour entrance or incoming tsunami waves. Seiches can cause damage in some marinas, harbours and bays.

Tsunamis are waves generated by submarine landslides, underwater volcanos or more commonly by earthquakes. They are difficult to predict after the initial disturbance has

occurred, but tsunami propagation modelling is constantly improving. Tsunamis can wreak havoc on coastal regions as their wave height increases considerably as they shoal in shallower waters towards the coast. *Tsunami* are episodic and driven by geological processes and are therefore usually treated separately from other sea-level processes.

A *storm surge* is the large-scale elevation of the ocean surface in a severe storm, generated by the low atmospheric pressure and the high wind speeds in the storm. The space and time scales of a storm surge are therefore roughly equal to the weather system generating the storm, such as a few hundred kilometres and over 1–2 days. Although the time scale of an individual storm is usually a couple of days, *storm surge* can be treated as weather-induced sea-level variability, which can include weather systems, or even several weather systems. The combined effect of inverse barometer and wind set-up produces storm surge. The inverse-barometer effect describes the sea-level response to atmospheric pressure changes: more specifically sea level temporarily rises in response to a decreasing atmospheric pressure and *vice versa*. In the open oceans, there is a direct isostatic inverted-barometer response relationship between sea level and barometric pressure: 1 hPa decrease in pressure (below the average barometric pressure) results in a 10 mm increase in sea level (and *vice versa*).

In shallower water around the New Zealand coast the average inverted-barometer response is somewhat less than isostatic (Goring 1995). Wind set-up describes the 'piling up' of water against the coast by an onshore wind or can occur when winds blow alongshore if the coast is to the left of the wind in the southern hemisphere e.g. south-westerly wind off Otago and Canterbury. The effect of wind stress on the sea surface increases inversely with depth and therefore is most important in shallow water (Pugh 2004). In New Zealand, storm surges generally only have damaging effects when they coincide with spring high tides. The combination of high tide + storm surge + the mean sea level for that month is known as *storm-tide* e.g., the event in Auckland on 23 January 2011 that caused inundation of several coastal suburbs.

The astronomical *tides* are caused by the gravitational attraction of solar bodies, primarily the sun and the Moon, with the Earth, which flow through to regular ocean-scale changes in sea level and currents. The periods of the dominant tidal components range from a few hours to a bit more than a day. In New Zealand the astronomical *tides* have by far the largest influence on sea level, followed by episodic storm surge (in most locations).

Figure 1.1 shows a power spectrum of the sea-level record measured at Sumner Head (Christchurch) between June 1994 and July 2009. The power spectral density on the *y*-axis is equivalent to the energy (variance) of the sea level oscillations in the measurements. Peaks in the power spectrum occur at particular frequencies (or

periods; period = 1/frequency). In Figure 1.1 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 (twice-daily) 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 Sumner Head, and this is true for most locations around the New Zealand coast. Smaller peaks are associated with diurnal (once daily) tides, and short-period over-tides (sometimes called 'tidal residual' or shallow-water tides). There is considerable energy at longer periods associated with storm surge, but because storm surge is not a regular sea level oscillation, nor at any characteristic period, there are no clear peaks, with the storm surge energy smeared across a range of periods (frequencies) in the power spectrum.

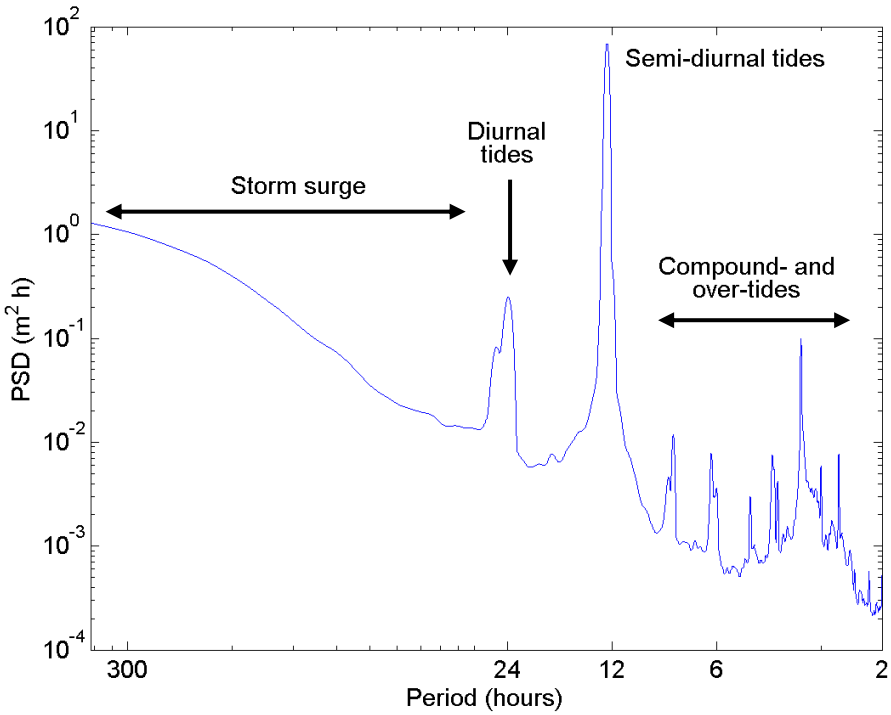

Figure 1.1: Power spectral density (PSD) of Sumner Head sea level from 1994 to 2009 versus period of sea-level oscillation (period = 1/frequency).

1.2 Climate-induced sea-level variability and change

Sea-level variability at timescales of 1 month or longer is generally referred to as variability in the *mean level of the sea* (MLOS), because it does not include short or long wave fluctuations. MLOS can be thought of as sea level after the various 'waves'

(described in section 1.1) have been averaged out. Variability in MLOS is driven by variability or changes in climate due primarily to:

- Seasonal (annual) heating and cooling of the ocean surface (0–100+ m) layer, and associated seasonal weather influences, especially from wind and barometric-pressure patterns;

- Interannual cycle due to El Niño Southern Oscillation (ENSO), comprising alternating El Niño and La Niña episodes;

- Inter-decadal cycles from the IPO (Inter-decadal Pacific Oscillation), which arise from decade-to-decade changes in the ENSO cycle; and

- Climate-change and long-term sea-level rise [see Tool 2.2.1].

The annual seasonal cycle in sea level is largely due to thermal heating in summer (causing thermal expansion of seawater) and cooling in winter (contraction).

El Niño is a natural feature of the Pacific climate system, but has a global influence. Originally it was the name given to the periodic development of unusually warm ocean waters along the tropical South American coast and out along the Equator to the dateline, but now it is more generally used to describe the whole 'El Niño – Southern Oscillation' (ENSO) phenomenon, the major systematic global climate fluctuation that occurs at the time of the ocean warming event. El Niño and La Niña refer to alternating episodes of the ENSO cycle, when major changes in the Pacific atmospheric and oceanic circulation occur. The strength of each episode is represented by the Southern Oscillation Index (SOI), which is calculated from the pressure difference between Tahiti and Darwin. Negative values of this index correspond to El Niño conditions (significant event if < -1), while the opposite conditions with an anomalously positive SOI value are called La Niña episodes. The ENSO cycle occurs about 2 to 5 years apart, with each episode typically becoming established around April or May and persisting for about a year thereafter. ENSO causes changes in water temperature and wind patterns that affect New Zealand sea levels and there is a strong relationship between MLOS and the SOI at interannual timescales.

The longer 20–30 year Inter-decadal Pacific Oscillation (IPO) is a longer background climate cycle arising from multi-decade variability in ENSO that also has positive and negative episodes. The Pacific is currently in a negative episode that enhances La Niña and diminishes El Niño occurrences. It affects the entire Pacific and appears to change relatively quickly to the opposite phase, often with a step jump in mean sea level.

In New Zealand the seasonal cycle can be up to about ±0.08 m variability in MLOS, ENSO leads to about ±0.12 m, and the IPO to about ±0.05 m. The total possible range in MLOS due to combined seasonal, ENSO and IPO cycles is therefore about ±0.25 m (Figure 1.2) – but doesn't include month-to month variability due to storminess or persistent anticyclonic weather. The Pacific is currently in a negative phase of the IPO.

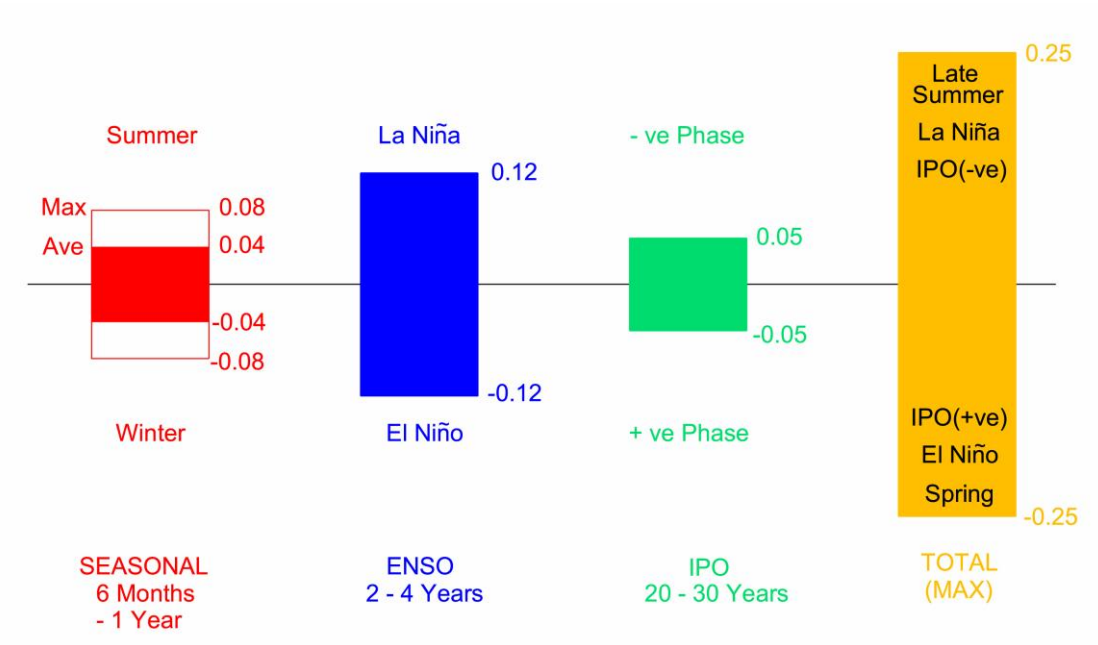

Figure 1.2: Variability in MLOS due to climate cycles.

1.3 Unravelling sea-level variability

Sea level responds to the various 'drivers' described in Sections 1.1 and 1.2. A sea-level record (a timeseries of sea-level measurements) may contain any of the processes described in Sections 1.1 and 1.2, depending on the sampling frequency (frequent enough to resolve short-period motion) and duration (long enough to resolve long-period variability) of measurement.

The sea-level measurements can be analysed to identify the contribution of any of these sea level drivers to the total sea-level variability, depending on the aims of the analysis. For example, ports or harbours are locations where infragravity waves and seiche strongly influence maritime activities and short-term coastal erosion, but these two processes might be irrelevant to the study of longer-term sea-level variability at an open-coast site.

The various components that contribute to the sea level variability can be separated out from the measured sea level. Figure 1.3 shows a decomposition of the Sumner Head sea level record into astronomical tide, storm surge and MLOS components.

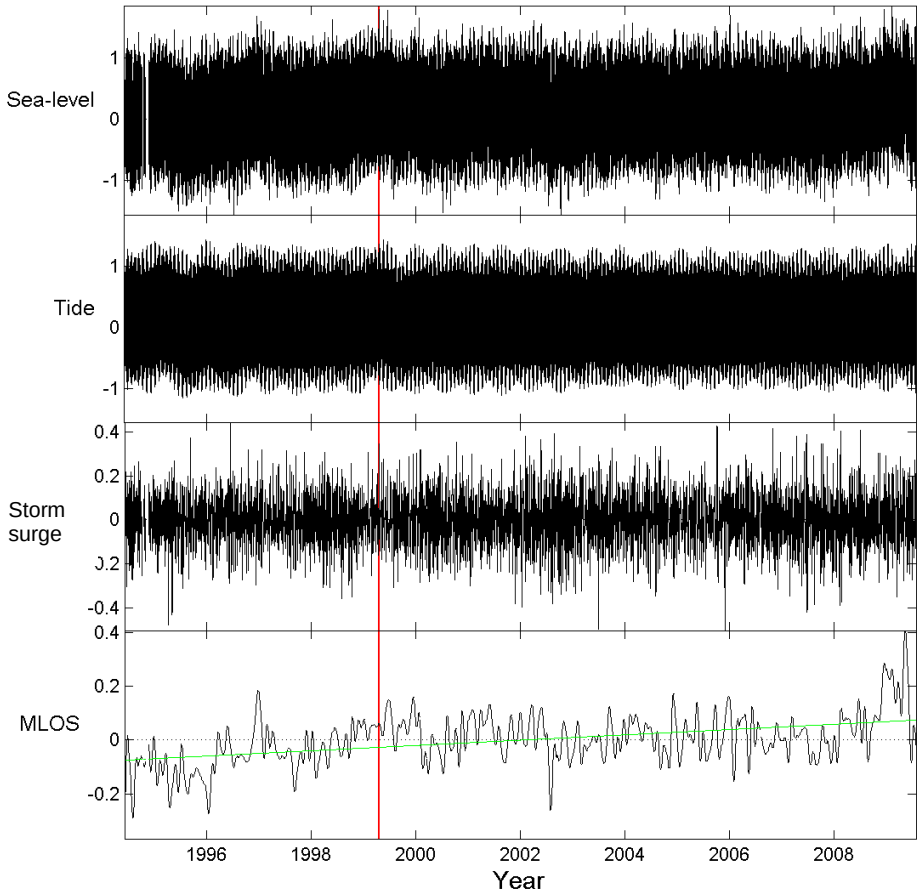

Figure 1.3: Components of Sumner Head sea level from a 15-year record. The vertical red line marks the 1999 Annual Maximum sea level, which is shown in more detail in Figure 1.4. The green line on the MLOS plot marks the sea level trend over the 15-year period.

It is useful to separate the measured sea level into its various components for reasons such as:

- Tidal harmonic analysis enables the tidal component of sea-level variability to be predicted for the future. The astronomical tide is the major cause of sea level variability in New Zealand, and tidal predictions are useful for navigation or general planning where sea level heights are important, such as

the "red alert" days when particularly high tides can combine with storms to create coastal inundation or erosion hazards[1].

- The various components occasionally combine to produce unusually high (or low) extreme sea levels. In New Zealand extreme high water is usually caused by the coincidence of a spring high tide and a storm surge, and the combined effect is known as a 'storm tide'. For example, Figure 1.4 shows the various sea level components that contributed to the 1999 Annual Maximum sea level, the second highest sea level on the Sumner Head record. At this time a relatively large storm surge coincided with a spring high tide and above-average MLOS. Some extreme sea-level analysis techniques require that the sea level be separated into components before analysis [see Tool 2.2.3].

- By removing the short-term variability associated with tides and meteorological disturbance, more detailed analysis of the non-tidal (or residual) component can be performed. As an example, the linear sea-level trend for the 15-year Sumner Head record has been analysed using the MLOS component, and overlaid on the MLOS component in Figure 1.3. The trend was a 150 mm rise over 15 years, or 10 mm/yr. Note that due to decadal variability, 15 years is much too short a period to determine a century-scale sea level trend such as climate-induced sea-level rise; normally this requires about 50 years of data. Sea levels in New Zealand have been rising at an average rate of 1.7±0.1 mm/yr over the last 100 years (Hannah 2004).

[1] See: http://www.niwa.co.nz/our-science/natural-hazards/research-projects/all/physical-hazards-affecting-coastal-margins-and-the-continental-shelf/dates

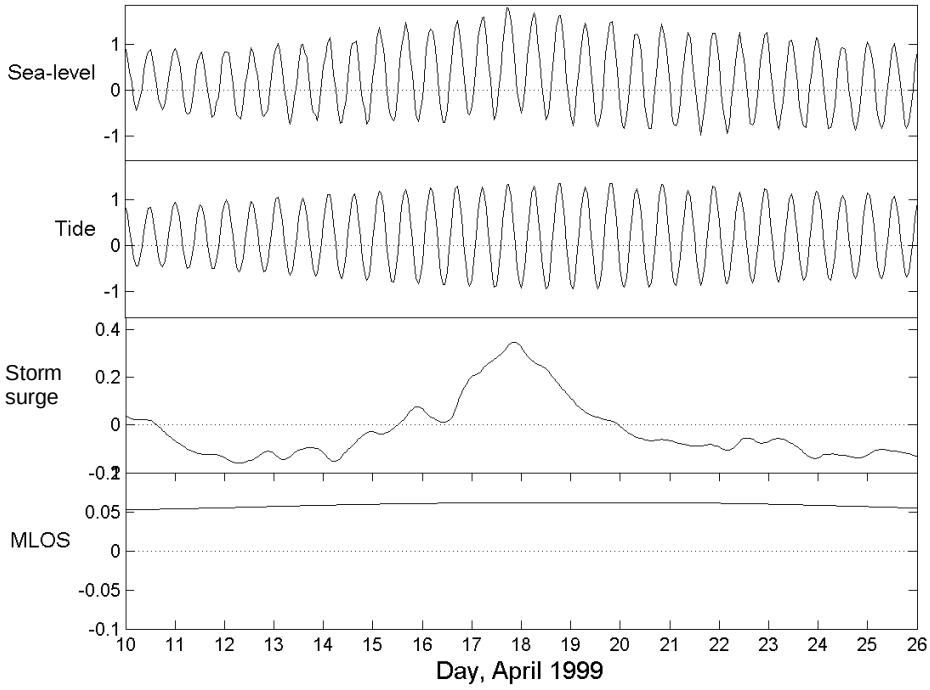

Figure 1.4: Components of Sumner Head sea level coinciding with the 1999 Annual Maximum sea level.

The steps involved in decomposing the sea level into its various constituent components are:

1. Undertake tidal harmonic analysis to obtain the deterministic (predictable) component of water level variability driven by the astronomical tides;

2. Subtract the tidal component from the sea level measurements to obtain the non-tidal (also called *residual*) component; and

3. Use a digital filter to separate the non-tidal residual into its various stochastic (random in time) components such as MLOS and storm surge. The filtering process can be performed in different ways (e.g., auto-correlation or spectral analysis), but is best undertaken using orthogonal wavelet decomposition that operates in both the time and frequency domains. Goring (2008) summarises the process of sea level filtering using orthogonal wavelet decomposition.

2. Tidal harmonic analysis and New Zealand tides

Tides in the main oceans are generated by gravitational forces exerted by both the Sun and Moon on the Earth. Ocean tide waves then propagate onto the continental shelf and into estuaries and harbours, being modified by wave shoaling (where the tidal wave slows down and increases in tide range as the water becomes shallower), friction from the seabed and constrictions such as estuary entrances, river mouths and straits.

Tides are entirely predictable (provided measurements or a verified tide model are available) and can be predicted for any day or period many years in advance.

The spring tide range (the difference between high and low waters) varies around New Zealand, reaching 3–4 m on the west coast but only 1–2 m on the east coast.

In a typical New Zealand sea level record, tidal variability is the largest part of sea level variability, and the first step in decomposing the measured sea level into its constituents is to identify and separate out the tidal component of variability. As seen in Figure 1.1, power spectra for the sea level record are characterised by a broad hump in a storm-surge band with a low-frequency (long-period) maximum and a decline at higher frequencies (shorter periods). Superimposed are a number of sharp tidal peaks near diurnal and semidiurnal frequencies (Pawlowicz et al. 2002).

Although tidal signals can be removed by standard high or bandpass filtering techniques, their relatively deterministic character and large amplitude makes classical harmonic analysis more effective. In classical harmonic analysis, the tidal signal is modelled as the sum of a finite set of sinusoids at specific frequencies related to astronomical parameters (Pawlowicz et al. 2002).

Commercial software and freeware are available for tidal harmonic analysis, an example being T_TIDE package of routines implemented in Matlab™, an analysis package widely used by oceanographers (Pawlowicz et al. 2002).

2.1 Definition of mean high water springs

Defining the position of mean high water springs (MHWS) is important as it is used to delineate the landward jurisdictional boundary of the Coastal Marine Area (CMA) under the Resource Management Act 1991 and the Foreshore and Seabed Act 2004. However, defining MHWS is not a straightforward task, particularly if an accurate

definition is required. There are a variety of quantitative and qualitative definitions of what constitutes a MHWS level in use (Ministry for the Environment 2008)[2]:

- MHWS: The traditional nautical approach is based on a quantitative 'tidal harmonic' definition of MHWS typically (Bell 2007, 2010) as the average of pairs of successive high waters in a 24-hour period in each semi-lunation (approximately every 14 days) at New and Full Moon (or in mathematical terms the sum of two main M2 (lunar) and S2 (solar) tide constituents). However, for central areas of the eastern coast of New Zealand, such a definition results in high tides that exceed such a MHWS level much more frequently than would be pragmatic for defining the boundary of the Coastal Marine Area (CMA).

- MHWPS: This upper-level MHWS is related to the higher combined perigean-spring tides that occur in clusters for a few days, peaking approximately every 7 months when a Full or New Moon coincide closely with the Moon's perigee.[3] They are colloquially referred to as 'king' tides. Around New Zealand, such a tide height is exceeded by between 3% and 12% of high tides.

- MHWS-10 and MHWS-12: These pragmatic definitions are based on an appropriate percentile of the high tides that would exceed a MHWS level. So, 10% of high tides exceed MHWS-10 and 12% of high tides exceed MHWS-12.

- Practical application of natural indicators: A range of natural indicators can be used to provide a qualitative assessment of MHWS, including toe of the dune, toe of the cliff, edge of vegetation, highest line of driftwood, tide marks on fence posts and, for estuaries, the seaward edge of glasswort (Salicornia australis) or other salt marsh plants.

Both Land Information New Zealand and the Environment Court have emphasised that there is no single definitive method that can be used to establish a natural boundary such as MHWS; the method used will have to depend on the particular technical or jurisdictional issue under consideration and natural characteristics of the location.

[2] See: http://www.mfe.govt.nz/publications/climate/coastal-hazards-climate-change-guidance-manual

[3] Perigee is the closest distance achieved between the Moon and Earth during the Moon's 27.5 day elliptical orbit around the Earth.

Figure 2.1 is an exceedance curve of predicted high tides for a 100-year period at Sumner Head, excluding any weather or climate related influence. It shows the different high-tide levels relative to gauge zero (which for the Sumner gauge is set to the Lyttleton Vertical Datum 1937) for different definitions of MHWS: MHWSn – traditional nautical approach; MHWS-10 – level exceeded by 10% of high tides; MHWPS – mean high water perigean-spring tide. Also shown are neap high tide markers (MHWNn, MHWAN) and the minimum and maximum predicted high tides.

The high tide exceedances plotted in Figure 2.1 are an example of the value of tidal harmonic analysis applied to a high-quality sea level record, enabling pragmatic definitions of MHWS (e.g., MHWS-10) to be calculated and applied. In open-coast locations where sea level measurements are unavailable, the NIWA tide forecasting model can be applied[4].

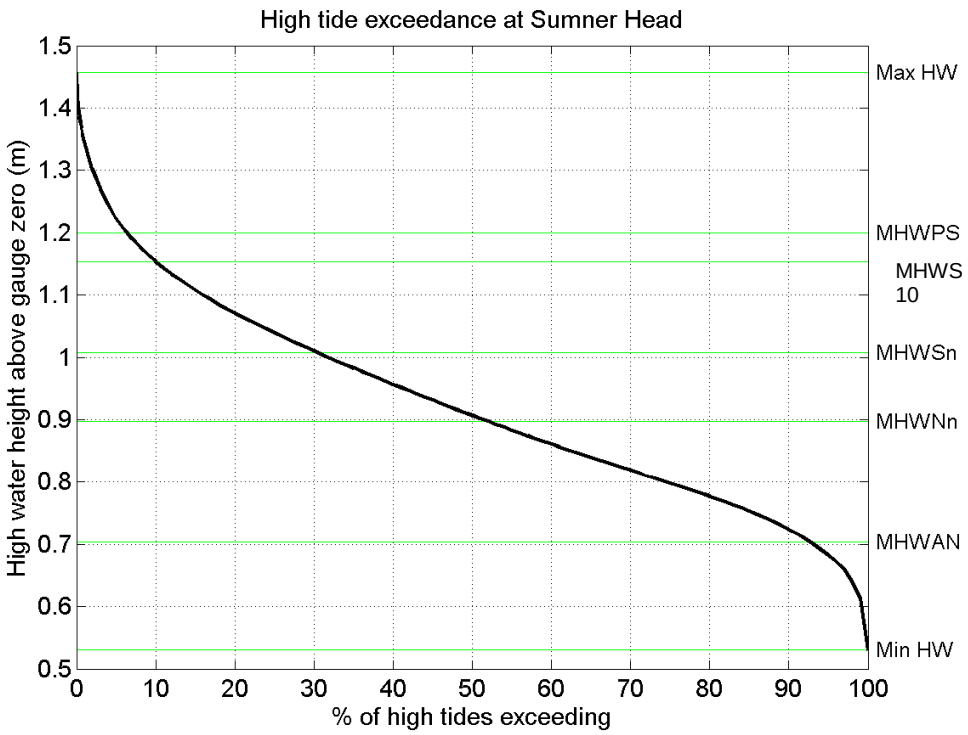

Figure 2.1: High tide exceedance at Sumner Head relative to gauge zero. Max HW = maximum high water; MHWPS = mean high water perigean spring ($M_2 + S_2 + N_2$); MHWS-10 = mean high water spring height exceeded by 10% of all tides; MHWSn = mean high water spring nautical ($M_2 + S_2$); MHWNn = mean high water neap nautical ($M_2 – S_2$); MHWAN = mean apogean neap ($M_2 – S_2 – N_2$); Min HW = minimum high water.

[4] See: http://www.niwa.co.nz/services/online-services/tide-forecaster

2.2 Red Alert days for coastal flooding

Most New Zealand cities are situated on the coast and many of these are beside rivers. Therefore, they are at risk from flooding, either from the sea itself, or from rivers discharging into the sea. If a storm surge or river flood occurs at the same time as the largest tides, serious flooding can occur. Yet, a major contributor to coastal flooding around New Zealand is upper-range high tides, which are deterministic and able to be forecast well in advance. Hence, estimates are easily made of dates during the year when the potential for coastal flooding is greatest – they occur a few days after Full or New Moon when the Moon is also closest to the Earth (in its perigee). These tides are called perigean-spring tides.

Thus, a set of red-alert dates can be generated when even a minor storm surge or river flood could cause coastal flooding in low-lying areas because the tides are extreme for those dates[5]. Conversely, another set of carefree dates can be generated when there is little danger of flooding at the coast unless a large storm surge or river flood occurs. Of course, a really major flood or storm surge event may cause coastal flooding at any time, no matter what the tide. No one is surprised when such large storm events cause flooding. However, many people were surprised on 17 April and 15 June 1999 when relatively minor storm surge events coincided exactly with perigean spring tides to cause widespread coastal flooding from Dargaville to Christchurch or similarly, the recent storm-tide inundation event in Auckland on the 23 January 2011. Yet these dates were predicted in a set of red-alert dates for that year.

3. Glossary

Mean level of the sea (MLOS) – The actual level of the sea over a specified averaging period (months, years, decades) after removing the tides (not to be confused with mean sea level or MSL, which often refers to a fixed vertical survey datum). Standard practice for obtaining MLOS involves filtering the non-tidal *residual* sea level component to remove variability with oscillation periods less than 1 month.

Mean sea level (MSL) – Mean sea level or local vertical survey datum, generally based on measurements of the mean level of the sea in the 1930s to 1950s for different regions. Because of the sea-level rise since then, MSL datum values around New Zealand are usually several centimetres below the current mean level of the sea (MLOS).

[5] See: http://www.niwa.co.nz/our-science/coasts/research-projects/all/physical-hazards-affecting-coastal-margins-and-the-continental-shelf/dates

Sea-level rise – Trend of annual mean sea level over timescales of at least five or more decades. Must be one of the following two types: eustatic – overall rise in absolute sea level in the ocean level; or relative – net rise relative to the local landmass on which a gauge sits (that may be subsiding or being uplifted).

Storm surge – The temporary elevation in the ocean surface above the level expected from the tidal variation alone at a given time and place. The temporary increase in the height of the sea is caused by extreme meteorological conditions such as low atmospheric pressure and/or strong winds, and so storm surge has motion timescales of 1.5–14-days. Conversely, negative storm surge or set-down occurs when high anticylonic conditions and/or offshore-directed winds are present.

Storm tide – The total elevated sea height at the coast above a datum during a storm, combining storm surge, monthly MLOS and the predicted astronomical tide height.

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