NSW EXTREME OCEAN WATER LEVELS

Final Report MHL2236
December 2018

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NSW Extreme Ocean Water Levels

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Foreword

This report has been prepared by NSW Government's Manly Hydraulic Laboratory (MHL) for the NSW Office of Environment and Heritage (OEH). The report presents the findings of an investigation into NSW water levels measured by the ocean tide network operated by MHL and funded by OEH. It follows on from MHL Report 1881 *NSW Tidal Anomaly Analysis*, presenting gauge analysis with longer datasets, a higher degree of quality coding and improved analyses.

We acknowledge senior engineering lecturer Dr Dave Callaghan from the University of Queensland for his significant contribution to this report, in particular the extreme value analysis of the data.

Executive summary

Understanding the magnitude and recurrence of the tidal climate, tidal anomalies and extreme sea level events is required for effective coastal management, including the assessment of coastal erosion, inundation and structural design.

This report is the result of a detailed investigation into tidal records collected and maintained by NSW Government's Manly Hydraulics Laboratory (MHL) on behalf of the NSW Office of Environment and Heritage (OEH). OEH manages an extensive network of automatic water level recorders as part of its Floodplain, Estuary and Coastal Management programs. Analysis of these records provides information on the tide climate of NSW, as well as tidal anomalies and long-term water level variability and cycles.

MHL records ocean water levels at 26 stations along the NSW coastline from Tweed Heads in the north to Eden in the south, comprising more than 30 years of continuous records, including five offshore open ocean stations, 11 onshore open ocean or open bay stations and 10 onshore river entrance stations. The offshore open ocean stations lack a common datum between deployments, and the onshore river entrance stations are affected by catchment runoff and changing river entrance conditions and, therefore, are not suitable for extreme value analysis of water levels. Onshore open ocean or open bay stations are the only station type within MHL's ocean tide network considered suitable for extreme value analysis (other than Patonga which could also be classified as an open bay station), the underlying characteristic being that onshore open ocean or open bay gauges remain largely unaffected by flood events and changing entrance conditions and, hence, provide the most reliable long-term extreme ocean water level trends for extreme value and water level anomaly analysis.

Two of the 11 onshore open ocean or open bay stations include East Australian Current influences and local effects, at Norfolk Island and Lord Howe Island, and hence have been excluded from the extreme value analysis presented in this report. The extreme value analysis results from Ulladulla, Sydney (Hunters Bay) and Port Hacking gauges have also been omitted from the key results presented in this report – Ulladulla due to its relatively short record length and the combination of two large events in that data that greatly broaden the confidence intervals of the extreme value fit, and Sydney (Hunters Bay) and Port Hacking, due to their proximity to the Fort Denison station. Results of extreme value analysis from these gauges are however provided with all other station results in **Appendix C.** Key results are presented for the remaining seven suitable ocean water level data stations including the addition of the Port Authority of New South Wales's Fort Denison station.

In the current study we examine several different methods for the calculation of extreme ocean water levels along the NSW coast. Continuous time series data are analysed from the seven suitable water level stations comprising Coffs Harbour, Crowdy Head, Port Stephens, Patonga, Fort Denison, Jervis Bay and Eden which span more than 30 years. With such a large data set, automatic techniques are sought to pre-process measurements and extract suitable input data for extreme value analysis. The approach adopted was to assess extreme value analysis methods for ocean water levels based on the longest quality controlled records for Fort Denison (more than 100 years) and apply the preferred method(s) to the other NSW stations characterised by shorter records (about 30 years).

The automatic extreme value analysis techniques used are influenced by the statistical method adopted. For example, statistical techniques using block maxima have relatively simple automatic methods to produce suitable input data. Other methods, however, require that extreme value selection be based on independent event occurrences, which requires more elaborate methods to produce suitable input data. Some uncertainties are also generated by the measurement methodology (sampling interval and averaging processes) which may influence the estimated water levels and residuals. Pre-processing techniques are further complicated for ocean water levels given that the tidal range is several times larger than the magnitude of tidal anomalies along the NSW coast and long period (inter-annual and inter-decadal) water level variability from oceanographic and climatic processes have magnitudes that can shift extreme ocean water level return periods significantly.

Harmonic analysis remains the accepted method of resolving the astronomical tide from the record. MHL typically performs this harmonic analysis on yearly records. The astronomical component is determined using harmonic tidal analysis. The non-astronomical component is determined by the difference between the measured and astronomical tide in the annual records. This is commonly referred to as the tidal residual, storm tide, storm surge, or setup/ set down.

Key Findings

The Fort Denison tide station was analysed to determine the magnitude of uncertainty from analysis methods and other climatic variability such as El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). For method uncertainties, block maxima using generalised extreme value distribution as well as peak-over-threshold and max-gradient approaches combined with Generalised Pareto were compared and found to agree within ± 0.1 m. For analysis method and climatic variability combined, uncertainty of 0.25 m has been estimated at the 100-year return period.

Use of detrending techniques to allow separation of the non-stationary effects from long-term sea level changes was shown to reduce the confidence interval range. This detrending of the Fort Denison record demonstrated only a small difference in extreme water levels and very minor effects on the tidal residuals.

Following the analysis of the Fort Denison tide station, the Generalised Pareto model was chosen for presentation of the extreme ocean water levels. **Table ES1** provides a summary of the 20-year and 100-year Average Recurrence Interval (ARI) extreme water levels along the NSW coastline using the Generalised Pareto (GP) model along upper and lower 95% confidence limits.

The estimated 20-year ARI extreme water levels vary from 1.25 m in the south of the state to 1.43 m in the north, and the 100-year ARI vary from 1.30 m in the south to 1.49 m in the north. This indicates an estimated 0.2 m decreasing trend in extreme ocean water levels from north to south along the NSW coastline as shown in **Figure ES1** with non-uniformities around Port Stephens and Patonga. Confidence intervals vary within 0.2 m for the 20-year ARI extreme ocean water levels and within 0.5 m for the 100-year ARI levels.

Table ES1 20-year and 100-year ARI extreme water level along the NSW coastline

Station	20-year ARI levels using GP (m AHD)			100-year ARI water level using GP (m AHD)		
	Model	Lower limit	Upper limit	Model	Lower limit	Upper limit
Coffs Harbour*	1.43	1.39	1.59	1.49	1.42	1.86
Crowdy Head*	1.38	1.35	1.46	1.43	1.39	1.56
Port Stephens	1.31	1.27	1.39	1.36	1.31	1.50
Patonga	1.39	1.35	1.48	1.43	1.39	1.59
Fort Denison	1.35	1.32	1.39	1.42	1.38	1.53
Jervis Bay	1.32	1.29	1.40	1.36	1.32	1.50
Eden	1.25	1.21	1.35	1.30	1.25	1.52

GP = Generalised Pareto model fit * low pass filter applied to known seiche-affected sites

The Fort Denison 100-year ARI is estimated to be 1.42 m. This indicates that the highest recorded water level at Fort Denison of 1.48 m AHD on 25 May 1974, based on more than 100 years of records, could be characterised by an ARI slightly greater than 100 years, as might be expected. It should be noted that the ARI for the 1974 event could range from between 50 years to greater than 200 years based on the confidence limits of the extreme value analysis.

Tidal planes analysis results for open bay and port locations along the NSW coast are shown in **Figure ES2.** Mean Sea Level (MSL) along the NSW coast is relatively consistent, within ±0.05 m AHD, except at Eden where MSL is approximately -0.09 m AHD. Alongshore variability in the upper tidal planes (HHWSS and MHWS) along the NSW coast may potentially account for some of the observed alongshore trends in extreme ocean water levels. It should be noted that the alongshore trends in extreme ocean water levels and tidal planes from north to south along the NSW coastline are not indicative of sea level rise trends.

Additional alongshore variability in extreme ocean water levels may also be attributed to non-astronomical components as shown by extreme tidal anomalies in **Figure ES3**. Port Stephens recorded the highest tidal anomalies for both the 20-year (0.55 m) and 100-year (0.67 m) ARI return periods. Jervis Bay recorded the lowest tidal anomalies for both the 20-year (0.43 m) and 100-year (0.47 m) ARI return periods. Higher anomalies are also recorded at seiche-affected sites including Coffs Harbour, Crowdy Head and Ulladulla. Low pass filters have been applied at water level gauges with known seiching.

Key Recommendations

- Maintain the continual data capture by MHL on all coastal port and bay stations to improve NSW extreme ocean water level analysis. Extreme water level fitting is shown to significantly improve with longer data records and increased sample size. Extreme ocean water level analysis for NSW should be regularly updated as the length of available data records increase.
- Investigate potential sites for placement of onshore open ocean and open bay stations north

of Port Macquarie to obtain an improved understanding of the ocean water level along the northern NSW coastline.

- Caution is required when extrapolating estimated extreme ocean water levels beyond the record length (typically 30 years in the present study). It is recommended that sampling, statistical method and climatic variability are considered when selecting appropriate design ocean stillwater levels. Depending on the consequences of exceedance and the ability for cost effective future adaptation, an appropriate contingency may be necessary to account for these uncertainties.
- Continue to examine the various uncertainties associated with extreme value analysis of ocean water levels including the limitations imposed by record length.
- Undertake case study designs using the information provided in this report to develop a methodology for typical case uses.
- Undertake further analysis of the recent high frequency logged data to provide a better understanding of the influence of sampling frequency and reduce the influence of local effects.
- Consider the use of filtering techniques such as low pass filters to pre-process data at all locations to remove signal noise at targeted frequencies associated with non-astronomical forces, wind waves and other short period waves.
- Consider detrending of the data to improve confidence interval and remove non-stationary factors (e.g., climate change). The effects of longer-term sea level rise and other potential effects associated with future climate change should be considered in the estimation of appropriate design water levels in NSW (based on the best available relevant science). Monitoring of mean sea level along the NSW coastline should be undertaken at regular intervals to observe any changes in temporal trends.
- Undertake exceedance-duration analysis to provide additional information on the probability that an extreme ocean water level event will exceed a threshold for a given duration.
- Investigate the effects of negative anomalies (set down) and undertake extreme value analysis of low waters. Most NSW port operations rely on accurate ocean water level predictions to determine under keel clearances and conditions under which the port may become inoperable. Extreme value analysis of low waters could provide valuable economic and environmental input to achieve more effective planning and operation of NSW ports.

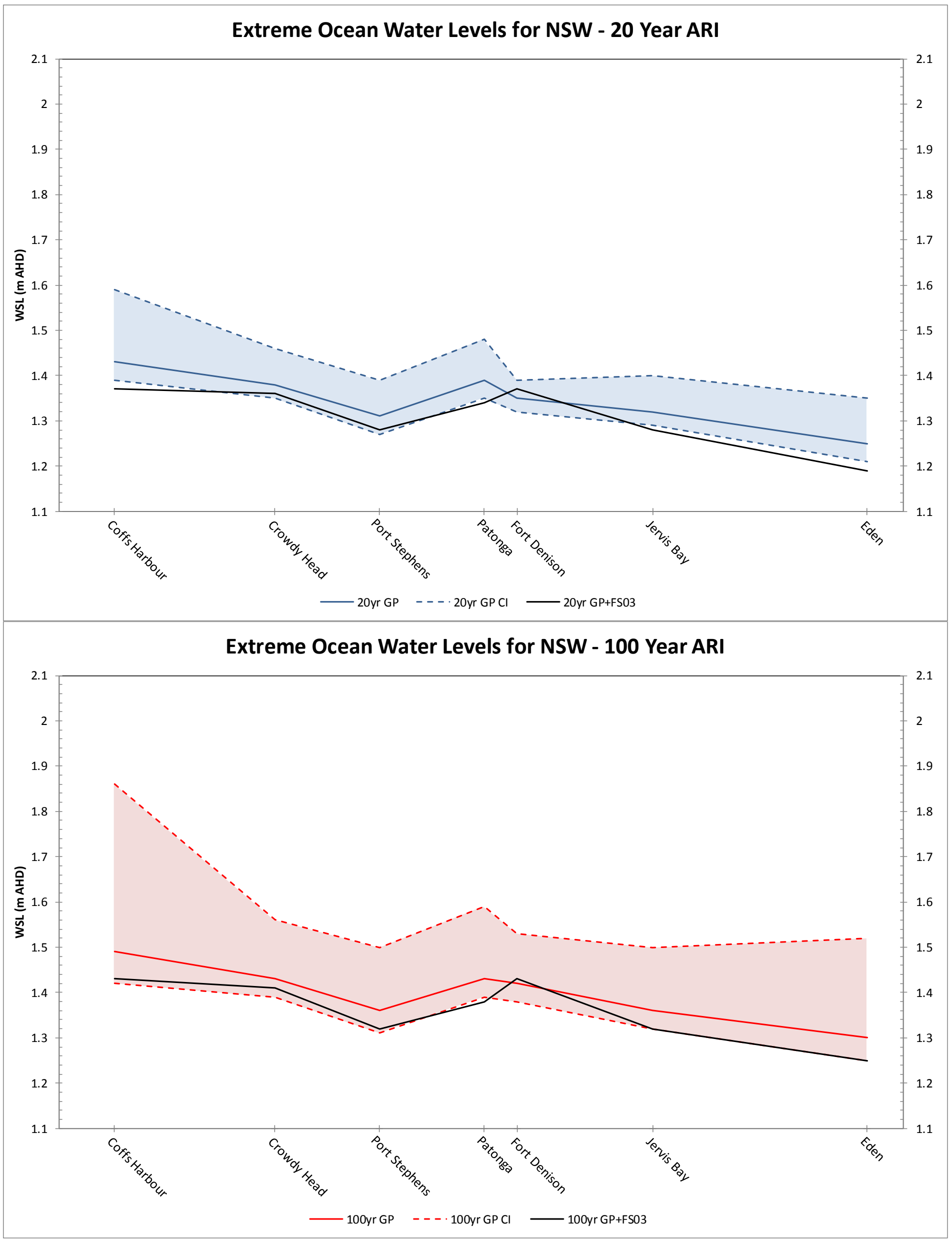

Figure ES1 Extreme ocean water levels along the NSW coastline

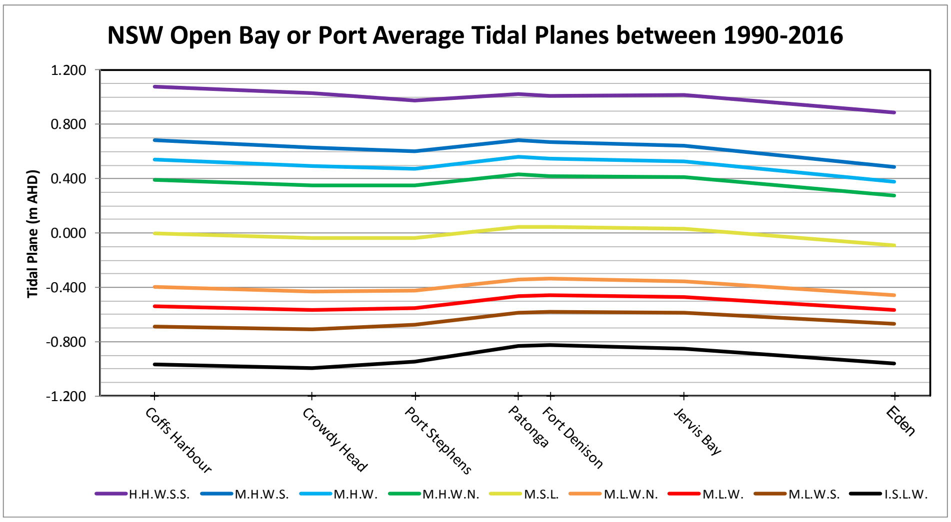

Figure ES2 NSW tidal planes

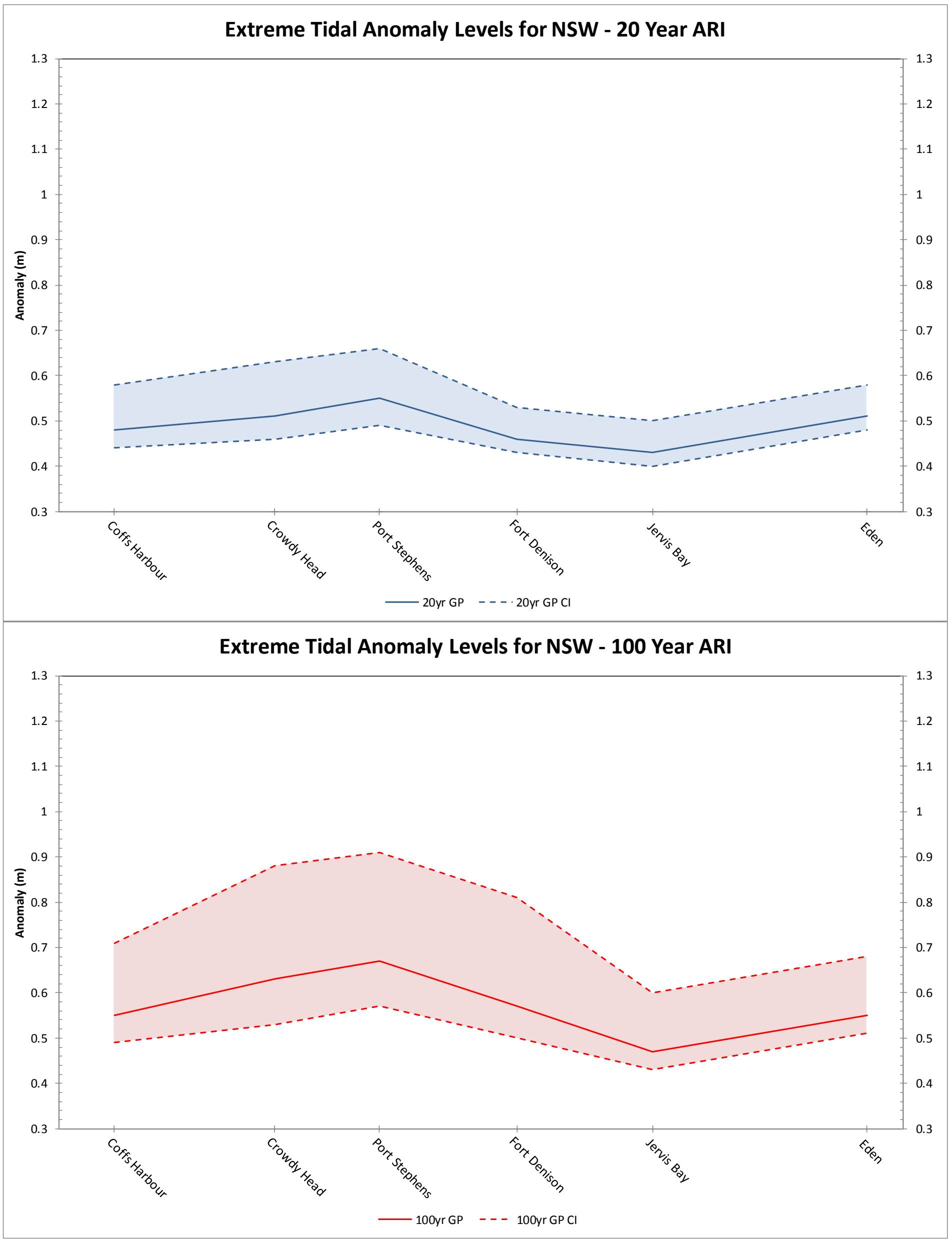

Figure ES3 Ocean tidal anomalies along the NSW coastline

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1. Introduction

1.1 Background

Tides on the NSW coast are subject to regular astronomical forcing and so can be forecast using established harmonic analysis techniques. However, measured water level data demonstrate that actual sea levels deviate from those predicted by harmonic analysis. These events are known as tidal anomalies and are caused by a range of oceanographic and meteorological effects. Understanding both the tide climate and the magnitude and recurrence of anomalies and extreme sea levels is an essential component of effective risk analysis, protection strategy, design and resource management for the NSW coast.

MHL has collected sea level data at coastal and estuarine sites along the NSW coast since the 1940s, and currently maintains a network of water level monitoring stations including over 200 permanent stations and over 100 short-term stations based in 34 coastal estuaries for the NSW Office of Environment and Heritage.

A comprehensive knowledge of the varying tidal responses along the NSW coast can be gained from the extensive network of tidal gauges. Both astronomical (tide generating) and a variety of non-astronomical forces influence the water level records at each site. This report investigates the extreme ocean water levels of the NSW coast and presents an assessment of specific drivers behind the major anomalous events.

1.2 Study Objectives

The objectives of this report are to:

1. provide an accurate and authoritative analysis of extreme water levels for use in planning, engineering and management of the NSW coastline
2. incorporate the best available tidal analysis programs and methods for the analysis of data
3. perform extreme value analysis on water levels to provide forecast extreme levels
4. discuss the state of knowledge of tidal anomalies and their drivers.

1.3 Previous Relevant Studies

A range of studies conducted by MHL has contributed to and provided supportive information for this report. For further information please refer to:

- MHL621 Sydney Region Tide-Storm Surge Analysis
- MHL1269 DNR NSW Tidal Planes Data Compilation Stage 3
- MHL1881 Tidal Anomaly Analysis
- MHL2179 Tide Gauge Histories
- MHL2156 MHL Tidal Methodology Review (Draft)
- MHL2100 Frequency Distribution
- MHL2053 Tidal Planes Analysis

- MHL Annual Summaries (1987–2013)
- MHL2336 Parramatta River Tidal Data Collection.

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2. Drivers of ocean water levels

2.1 General factors influencing ocean water levels

2.1.1 Astronomic tide

Astronomical tides along the NSW coast rise and fall twice daily (semi-diurnal tides) which is typical of many other open ocean coasts around the globe. The primary forcing is from the gravitational pull of the moon, being twice that of the sun and the centrifugal force from the earth’s surface. The relative positions of the earth, moon and sun affect tide levels, where high tides occur when the moon is either closet to or furthest (on the opposite side) from a particular region on earth. Low tides occur when the moon’s relative position is 90 degrees on either side of a particular region on earth, being characterised by the least net gravitational/centrifugal influence.

In developing an understanding of astronomical tides, we need to consider the different time scales which operate. As the earth rotates on its own axis every 24 hours, the moon’s relative position creates two high and two low tides each day. But the moon also orbits the earth, in the same direction that the earth rotates, every 28 days, so that the moon effectively reaches the same location on earth every 24 hours and approximately 50 minutes (every 24 hours plus 1/28th of a day). Hence, the high (or low) tide each day occurs about 50 minutes later each subsequent day. Within the 28-day lunar cycle, the earth, moon and the sun become in alignment every 14 days (concurrent and opposing), which results in an increased net gravitational/centrifugal effect with a resulting increased tidal range termed Spring tide. During the alternate 14-day period, when the earth, moon and sun are at right angles to each other, a smaller tidal range is experienced and is termed the Neap tide (refer to **Figure 2.1**).

Further to the semi-diurnal and Spring/Neap tide cycles, the summer/winter cycle affects the magnitude of the earth’s tides. Because the earth’s rotation is inclined (at 23.5 degrees) relative to its orbit around the sun, and because the earth’s orbit around the sun is not circular, but elliptical, the net gravitational/centrifugal force of the sun on earth is maximised during the summer perihelion and winter aphelion when the earth is closest and furthest from the sun respectively resulting in the maximum tides in a year (in early January and July respectively for the southern hemisphere and conversely in the northern hemisphere) commonly termed King tides.

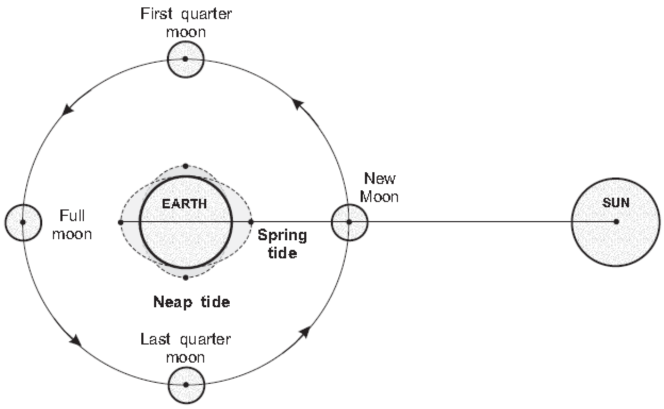

Figure 2.1 The influence of the earth, moon and sun alignment on tides

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The longer-term astronomical cycle is further complicated by the fact that the planetary orbits are both elliptical, eccentric and inclined resulting in the earth/moon orbital planes re-aligning every 18.6 years which is termed the Tidal Epoch. That is, the plane of the moon's orbit tilts at an angle of about 5 degrees relative to the plane on which earth rotates the sun (the ecliptic plane); not the equatorial plane on which the earth spins which is 23.5 degrees to the ecliptic plane. The moon's orbit relative to the sun completes 360 degrees and returns to the same location every 18.6 years, being ±5 degrees relative to the ecliptic or going from 28.5 degrees to 18.5 degrees in north-south orbit every 9.3 years.

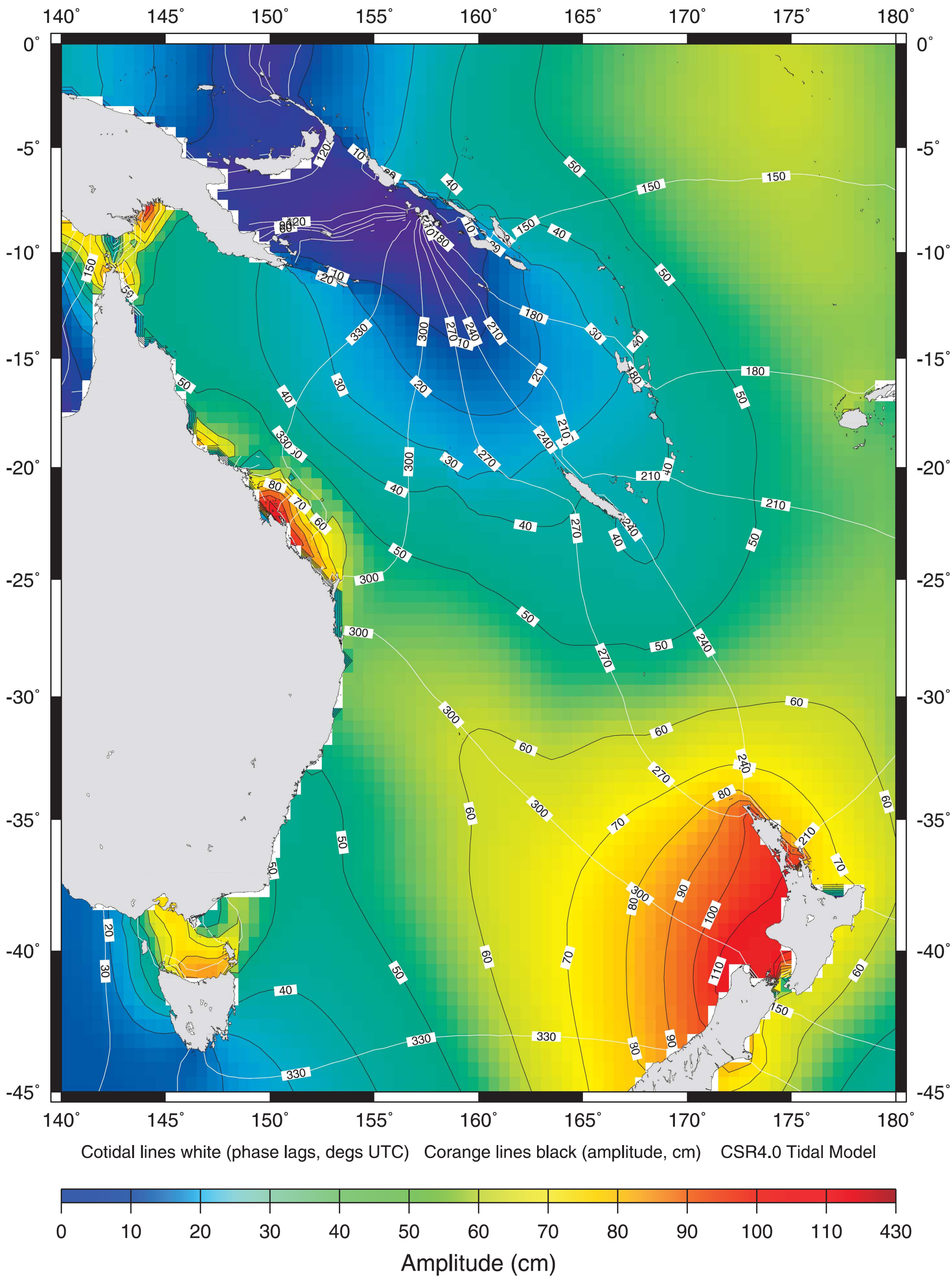
Beyond the Tidal Epoch, even longer term astronomical cycles have been identified, including precession of the equinox, where the earth's relative inclination to its plane of rotation around the sun (ecliptic plane) wobbles between 22.5 degrees and 24.5 degrees (presently at 23.5 degrees) about every 41,000 years. This phenomena is mostly related to the relative position of Jupiter's orbit and has been linked to global glaciations (ice ages) that are understood to occur in even longer cycles of some 100,000+ years as first described by Milankovitch in the 1920's (Hays et.al., 1976).

All of these astronomical variations modify the daily heights of the high and low tides so the tidal range varies by a slight amount from one year to the next. Changes within the Tidal Epoch are important when calculating average tidal conditions such as mean sea level or mean tidal range. Longer-term changes beyond the Tidal Epoch can be major due to associated glaciation effects with paleo records indicating sea level changes of more than 100 metres, albeit occurring over millennia rather than decadal temporal scales.

The ensuing oscillations of the tides propagate around the basins and affect the basin margins, continental shelves and coastal seas in different ways. The response of a shelf sea depends on its size, shape and water depth. Large tides occur near resonance where a natural mode of oscillation of part of the region has a period close to that of a constituent of the tide. A simple resonant case occurs when the shelf width or length of the basin corresponds to a quarter wavelength of the tide. Generally, each tidal constituent propagates as a wave forming a linked system, losing energy in shelf seas through dissipation by bottom friction and transferring energy to harmonics and other tidal frequencies through non-linear shallow water processes and interactions (Flather et al., 2001).

The general tidal characteristics of the western South Pacific form the context for the NSW coastal region. The tides at the coast will be determined by a combination of the tides offshore and the influence of local bathymetry. Numerical tide modelling by the National Tide Centre (Bureau of Meteorology) provides further insight into Australian tides. The resulting amplitude and phase plots of the four major tidal constituents (M2, S2, O1 and K1, described in detail in **Section 4**) are provided in **Figures 2.2–2.4**. The semi-diurnal M2 constituent dominates the tidal signal and is almost uniform along the NSW coast, while the influence of the other constituents contributes to a minor increase in amplitude and phase lag northwards along the coast.

M2 Tide



Cotidal lines white (phase lags, degs UTC) Corange lines black (amplitude, cm) CSR4.0 Tidal Model

Source: figure provided courtesy of National Tidal Centre, Bureau of Meteorology

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WESTERN PACIFIC CO-TIDAL AND CO-RANGE
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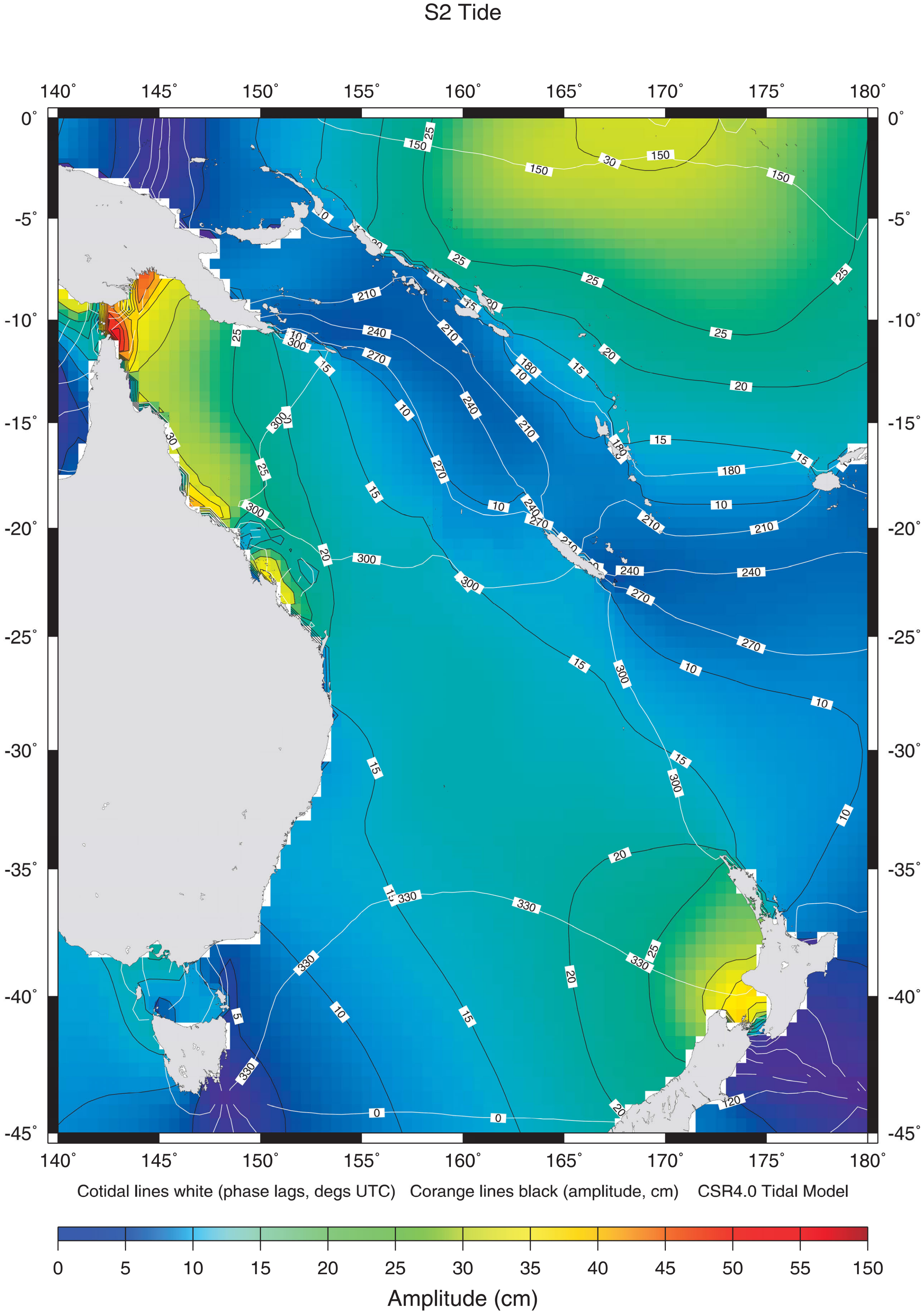

Source: figure provided courtesy of National Tidal Centre, Bureau of Meteorology

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WESTERN PACIFIC CO-TIDAL AND CO-RANGE
LINES FOR CONSTITUENT S2

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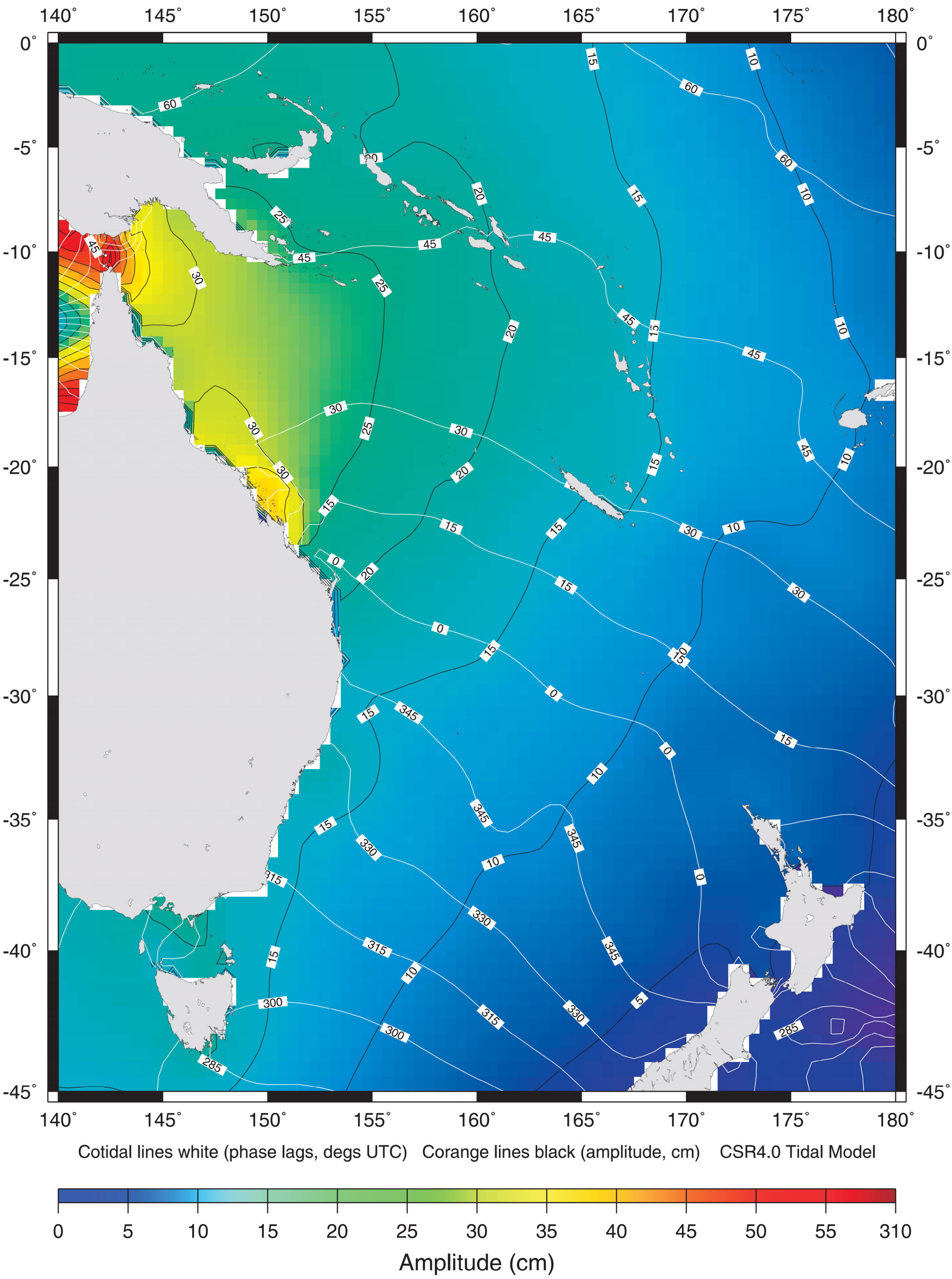
Drawing 2236-2.CDR

K1 Tide



Cotidal lines white (phase lags, degs UTC) Corange lines black (amplitude, cm) CSR4.0 Tidal Model

Source: figure provided courtesy of National Tidal Centre, Bureau of Meteorology

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WESTERN PACIFIC CO-TIDAL AND CO-RANGE LINES FOR CONSTITUENT K1

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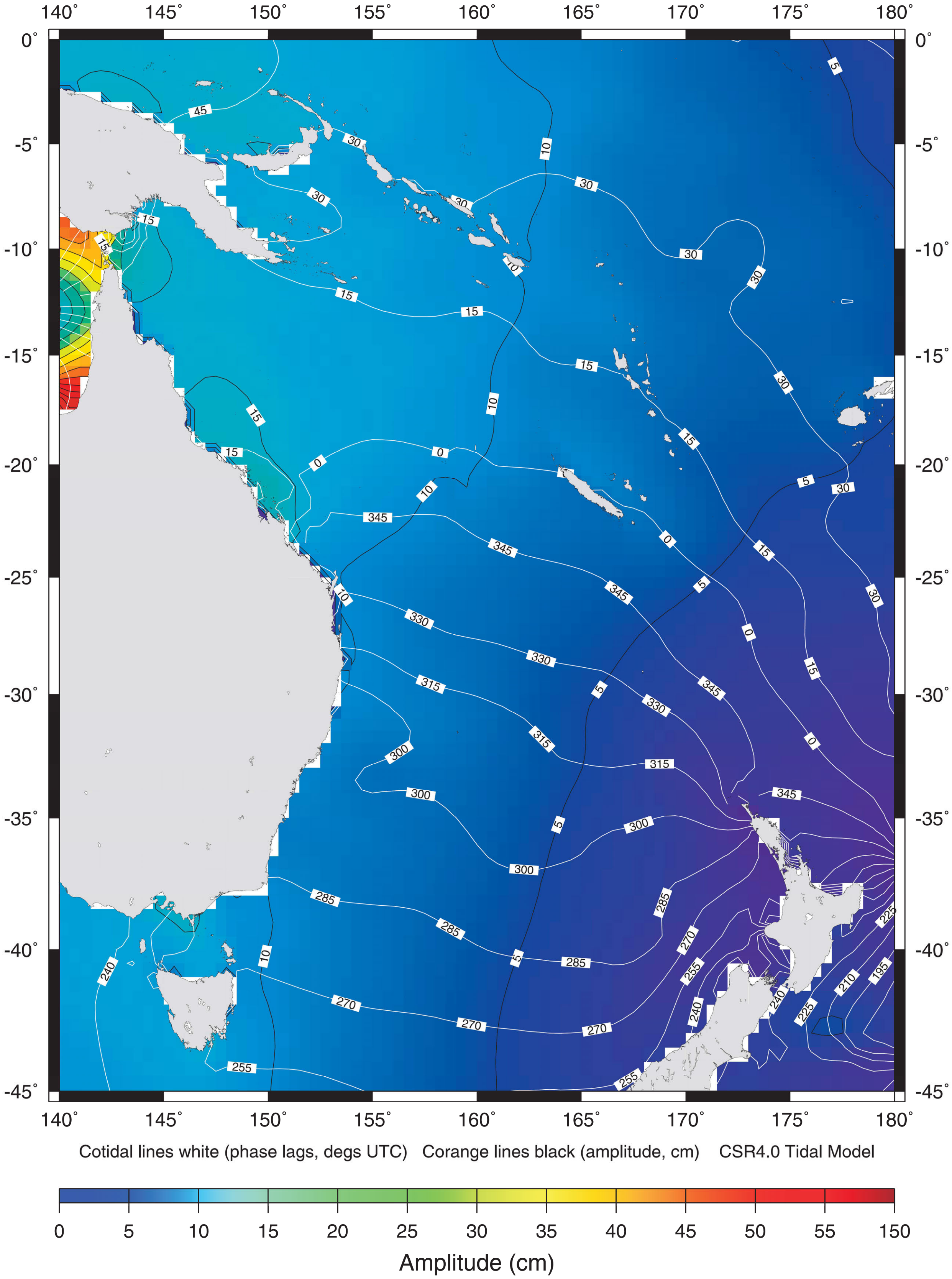
O1 Tide



Cotidal lines white (phase lags, degs UTC) Corange lines black (amplitude, cm) CSR4.0 Tidal Model

Source: figure provided courtesy of National Tidal Centre, Bureau of Meteorology

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WESTERN PACIFIC CO-TIDAL AND CO-RANGE LINES FOR CONSTITUENT O1

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Drawing 2236-2.CDR

2.1.2 Non-astronomic factors

Non-astronomic forces on tidal levels include oceanographic, meteorological and hydrographic effects, and a summary of these possible influences is provided below (see also MHL, 2003, Flather et al., 2001).

- **Seiches** – Stationary waves usually caused by strong winds, changes in barometric pressure and/or long period ocean wave forcing. Seiches can occur in lakes, semi-enclosed bodies of water, or in areas of the open ocean. Along the NSW coast, seiches typically occur with periods of 5 minutes to 2 hours. A low pass filtering technique was applied to reduce noise at these frequencies at water level gauges with known seiching including Coffs Harbour, Crowdy Head and Ulladulla.
- **Tsunamis** – A shallow water progressive wave, potentially catastrophic, caused by underwater seismic activity (submarine earthquake or volcanic eruption). These are common on the NSW coast but usually at very low amplitude. Meteotsunamis also occur along the coastline as described in MHL2475.
- **Barometric Effect** – The adjustment of ocean water level to changes in atmospheric pressure. Low pressure cells cause a rise in ocean water level, whereas high pressure cells cause a drop in ocean water level.
- **Wind Stress** – The shear stress exerted on the ocean water surface by wind. Surface wind stress results in a raised water level downwind when a shoreline is present. When combined with barometric effect it is called storm surge.
- **Wave Setup** – The increase in water level within the surf zone above mean still water level caused by wave breaking and mass transport of broken surf bore waters onshore. The resulting super-elevated waters along the shoreline result in undertow and rip currents that drive a seaward return of water.
- **Hydrologic Input** – Heavy localised rainfall resulting in raised water levels. Effect is greater in rivers or contained water bodies.
- **Ocean Currents** – Ocean currents are capable of raising the water level for extended periods by transporting large quantities of water onshore (e.g., migration of eddy currents along a coastline).
- **Steric Effects** – The adjustment of water level to changes in density (temperature and salinity). Changes are most pronounced in shallow waters.
- **Coastally Trapped Waves** – Long period waves with periods of days to weeks, generated by strong wind events on the southern Australian coastline and Bass Strait. Turning to the left of the direction of propagation by the Coriolis Effect, long period waves are trapped against the NSW coast as they travel northwards.
- **Sedimentation** – Sediment infilling from the coastal zone and catchment sources at river and estuary sites may lead to shallowing of the waterway, with effects on tidal constituents.
- **Bathymetry** – Configuration of the coastline and ocean floor bathymetry may play an important role in affecting tidal range and phase.

2.2 Key drivers of tidal anomalies

This section describes the key drivers of tidal anomalies in detail and describes the theoretical explanations of their impact on sea level. Details of the methodology used to extract the anomaly from the tide record are given in **Section 4**.

2.2.1 Inverse barometer effect

The inverse barometer effect is the impact of variable atmospheric pressure on the sea level for a stationary field, given by:

$$\eta=-1/\rho g(P - P_{ref}) \qquad (2.1)$$

η is the deviation in sea-surface height,
$P - P_{ref}$ is the deviation in atmospheric pressure,
ρ is the ocean water density,
g is the gravitational acceleration.

This approximately equates to 1 cm rise in sea level per 1 hectopascal drop in barometric pressure.

A rise (or depression) in sea level induces geostrophic flow to balance the surface gradient, generating large eddies hundreds of kilometres wide. For the southern hemisphere, flow is anti-clockwise around a high water level. The simple relationship between sea level and atmospheric pressure can therefore be complicated by bathymetry and shoreline effects in the coastal region, or by interactions with other ocean flows.

The relationship between atmospheric pressure and sea level is further complicated by changing atmospheric pressure (Nielsen, 2009). Travelling pressure systems or changing intensities will induce surface waves on synoptic scales (with small amplitudes and long periods) that propagate away from the low-pressure system.

2.2.2 Wave setup

Wave setup occurs as breaking waves drive energy towards the shore, causing a rise in mean sea level. This can be up to 1.5 m on the NSW open coast (NSW Government, 1990). The non-linear motion of waves in the breaker zone causes a net transfer of energy towards the coast. Rips and currents along the sea floor return the water seaward.

The impact of wave setup can be highly variable dependent on bathymetry within the surf zone, tide conditions (ebb or flood tide), wave conditions and other factors making it difficult to forecast wave setup in any location. We are yet to collect measurements in shallow water entrances (Callaghan, 2013) and subsequent debate amongst researchers about the relevance of wave setup in some coastal locations such as river and lake entrances, where many tide gauges are located, is still ongoing.

2.2.3 Wind setup

Wind setup is caused by wind shear against the surface of water driving the surface layer downwind, generating a surface gradient with raised water level at the downwind boundary. This setup only occurs where there is a boundary to restrict the flow, if no boundary exists then a downwind current exists but no setup.

The theoretical setup at the coastline can be determined by Nielsen (2009):

$$\overline{\eta}(h_2) = \alpha_v \frac{\tau_w}{\rho g} \frac{W}{h_1} \ln \frac{h_1}{h_2} \tag{2.2}$$

where $\overline{\eta}$ is the level of setup, α_v is eddy viscosity, τ_w is the wind shear, ρ is the water density, g is gravity, W is the shelf width, h_1 and h_2 are the offshore and nearshore water depths respectively. This shows that wider and shallower shelfs give higher wind setup (due to the restriction of the return flow at the sea bed), as do higher wind events. This would indicate that the far north coast of NSW is more prone to this form of setup, resulting from strong onshore winds associated with cyclones in the Pacific Ocean and the wider shelf that exists in northern NSW.

Ekman Transport

A secondary effect of wind-driven current flows is Ekman transport. Wind acting on the sea surface generates a surface current in the same direction as the wind shear. Energy is transferred progressively from higher levels to lower levels of the water column over time. If this acts for a long period (with surface currents over a large area) the rotation of the earth causes a deflection of the current in the water column to the left (southern hemisphere). This results in a spiralling of the current vector through the water column. The net current resulting from a fully developed Ekman spiral is theoretically 90° to the left (right) of the wind direction for the southern (northern) hemisphere, but is considerably less than this in practical applications.

McInnes & Hubbard (2001) showed that sustained southerly wind conditions over several days can generate setup on the NSW coast. This was attributed to Ekman transport diverting the wind-induced surface current towards the coast. The inverse is also true, where northerly winds generate an offshore surface current. This is associated with cold water upwellings as deep waters rise to replace the surface water

2.2.4 Coastally trapped waves

Coastally trapped waves (CTW) are long-period free waves that, due to rotational effects of the earth, travel anti-clockwise around the Australian continent. CTWs are generated by wind stress; in NSW this is predominantly from high wind events in Bass Strait. Coastally trapped waves are an important mechanism in the generation and suppression of upwelling events (Middleton & Leth, 2004) and so influence coastal ecosystems and weather. The propagation of CTWs northwards along the NSW coastline is affected by the East Australian Current (EAC) and associated eddies below the separation point north of Port Stephens.

NSW has the rare privilege of having had an experiment dedicated to the examination of the dynamics of coastally trapped waves. In 1983–84 The Australian Coastal Experiment (ACE) aimed to identify CTWs and their characteristics. Instrument arrays were placed in three shore-normal lines (at Cape Howe, Stanwell Park and Newcastle) to capture currents generated by passing CTWs, and so characterise CTW in the region.

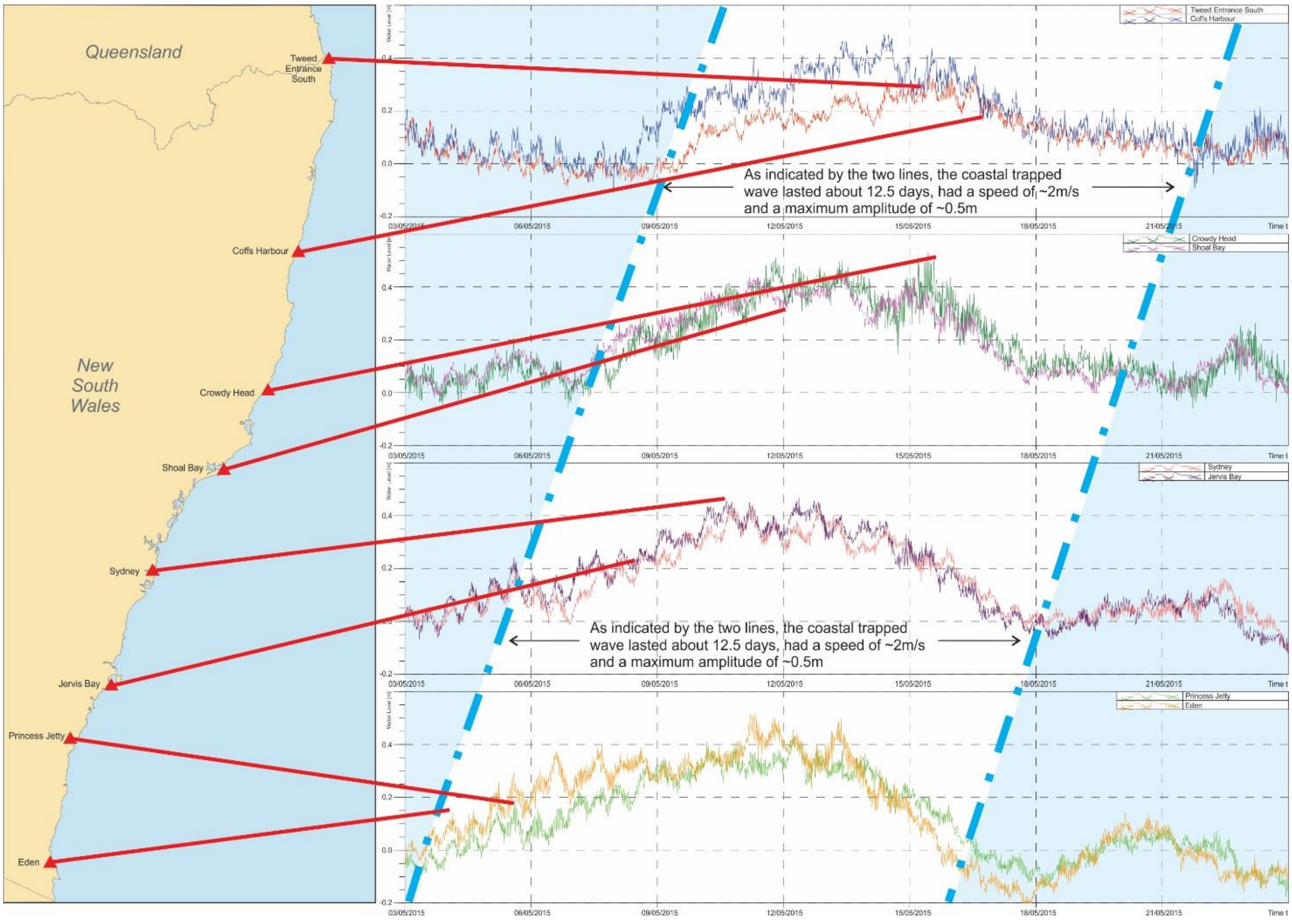
The source of CTW can be as far away as the Great Australian Bight, travelling through Bass Strait rather than around Tasmania (Church and Freeland, 1987). However, it has been shown that the majority of CTW energy is generated by wind events in the Strait. A second mechanism for the generation of CTWs in NSW may be by shore-parallel winds, however the relative energy between Cape Howe and Stanwell Park would indicate that there is not significant generation of CTWs within NSW itself. Sea level variation due to CTW was shown to be 65% of total sea level anomaly at Cape Howe, 40% for Stanwell Park and 24% for Newcastle.

Spectral analysis shows that the majority of the long period energy at Cape Howe and Stanwell Park is in the range 4–12 days. Phase speeds increase northward along the NSW coast due to increased stratification and increased shelf width (Church et al., 1986a), with mode 1 phase velocity 3.2-5.2 m/s, mode 2 phase velocity 1.8-2.4 m/s and mode 3 phase velocity at 1–1.2 m/s. Early analysis showed the second mode to be the dominant mode (Church et al. 1986a), but this unusual result was revised by subsequent analysis by McIntosh and Schahinger (1994) which showed that the first mode dominates.

Maiwa et al. (2010) found CTWs to have an annual pattern, with amplitudes distinctly larger in winter than in summer and a range of propagation speeds as 4.5 m/s ‘or faster’ on the western and southern coasts, and 2.1–3.6 m/s on the east coast, with a typical period of 1 to 2 weeks. They found that reinforcement of the CTWs by the wind forcing in the southern part of the eastern coast is necessary to obtain larger amplitudes of CTWs on the eastern coast. Woodham et al. (2013) compared tide gauge data with SSH data from BoM Bluelink data and found close agreement. Applying SSH data from the Bluelink forecasting system Woodham et al. (2013) concluded that CTWs propagate as continuous features between the south-west and north-east Australian coast from one end of this expanse of coastline to the other. They found the CTW amplitudes, phase speed and periods were consistent with previous studies, and that CTWs travelled faster and had greater wavelengths where the continental shelf is wider and that their amplitude is greater along the south coast than on the east coast. The role of wind forcing in Bass Strait was investigated and Woodham et al. (2013) concluded whilst there are some examples where anomalies were caused by wind forcing ‘the majority of SSH variations at CTW frequencies propagate as continuous features between the south-west and north-west corners of the Australian Coast’.

MHL2384 (2015) highlighted the occurrence of a coastally trapped wave event in May 2015. Due to the presence of a number of cold fronts, the CTW may have originated in the south-west and propagated to Bass Strait where it was reinforced by the wind and continued up the NSW east coast. The CTW was clearly evident in the ocean tide station records. The effect of the wave on the water level can be observed by viewing the residual (predicted – recorded) tidal data plot. The residual water level plots for Tweed Entrance South, Coffs Harbour, Crowdy Head, Shoal Bay, Sydney, Jervis Bay, Princess Jetty and Eden between 3 May and 20 May 2015 are shown in **Figure 2.6**. The CTW can be seen propagating from south to north. The lines on the figure indicate the residual water level due to the coastally trapped wave progressing northward along the coast. The maximum amplitude of the residual is around 0.5 m but varies along the coast. Using the guidelines on the graph as a rough estimate the CTW lasted about 12.5 days and had an average speed of approximately 2 m/s. This is consistent with the findings of other researchers as summarised above.

While absolute water levels on the open coast during this event were not particularly high (peak water level of 1.09 m AHD on the Sydney gauge), water levels within some coastal lake systems became significantly elevated compared with normal tides. In Lake Macquarie, even low tide levels were higher than normal high tide levels, with some foreshore and local street inundation. MHL (2013) found that at Lake Macquarie ‘for longer anomaly events there is very little attenuation of the anomaly. Shorter duration anomaly peaks do not fully propagate past the lake entrance, with some attenuation observed.’ This becomes significant as diurnal and semi-diurnal tidal constituents in these systems are reduced compared with the ocean resulting in a very much reduced tide range. Collins et al. (2012) observed that for large water bodies (such as Lake Macquarie) near the ocean entrance, anomalies of a few days have a pumping effect on the lake level.



As indicated by the two lines, the coastal trapped wave lasted about 12.5 days, had a speed of ~2m/s and a maximum amplitude of ~0.5m

As indicated by the two lines, the coastal trapped wave lasted about 12.5 days, had a speed of ~2m/s and a maximum amplitude of ~0.5m

Figure 2.6 Coastally trapped wave along the NSW coastline in May 2015 (MHL2384)

2.2.5 Ocean currents and eddies

Variations to deep ocean circulations can impact the coast, driving changes to coastal water levels. For NSW, the main cause is the strong East Australian Current (EAC), which brings warm tropical water down to the more temperate Tasman Sea. This travels southwards, close to the coast on the ocean shelf until some point north of Port Stephens where it separates from the coast. The separation, along with the temperature differential, drives turbulent eddies into the Tasman Sea. These eddies can persist for months and travel throughout the Tasman, covering the mid to south coast of NSW to New Zealand. They can be cyclonic or anti-cyclonic causing setup and set down of water levels which can impact coastal water levels. Other circulations may be present that also impact the coast, but are not so well understood.

2.2.6 Long-term variability

Water levels are known to vary over periods of decades to centuries. Much of this variability is not well understood, but there has been some progress in correlating variations to other climatic indices. For example, it was shown in MHL1881 that a strong correlation exists between ENSO/SOI cycles and water levels in NSW. This is, however, an imperfect correlation, and further work is required to understand the mechanisms that drive this long-term variability.

Holbrook et al. (2011) determined that the ENSO to decadal variations and the ocean-adjusted multi-decadal trend in observed sea level at Fort Denison tide gauge are strongly connected to modulations of the EAC transports by incoming westward-propagating oceanic Rossby waves (wave generated by the rotation of the planet). It demonstrated a connection between regional- and large-scale wind stress-forced Rossby waves and the variability in EAC transports and sea level in Sydney.

White et al. (2014) confirmed that a large part of the inter-annual and decadal variability in sea level around Australia is significantly correlated with the ENSO/SOI and a relationship can be expressed as an empirical function. Using the two longest tide gauges on record in Sydney and Fremantle, it was found that since 1993 MSL trends have been higher than the global mean around northern Australia and similar to the global mean around southern Australia. Higher sea level trends in northern Australia are largely associated with natural climate variability. Following removal of the effects of this natural variability, the majority of Australia's coastline still showed an increased rate of rise from the early 1990s, consistent with global mean trends.

Sea level rise associated with global climate change is another important variation in sea levels. This is a complex phenomenon largely outside the scope of this project. There are many other drivers of sea level variability that operate on years to decadal scales that obscure sea level trends, and the stations used in this report (apart from Fort Denison) are too short for the analysis of sea level rise. It is, however, an important consideration in the analysis – for example, the Fort Denison data needed to be linearly detrended before performing the extreme value analysis, to prevent the trend from affecting the results. This was not required for the shorter datasets.

3. Tidal data collection stations and instrumentation

3.1 Site classification and details

MHL maintains 26 ocean tide monitoring stations on the NSW coast from Tweed Heads in the north to Eden in the south, comprising more than 30 years of continuous records. To provide an overview of the location of the stations, a summary map of the NSW coastline and locations of the gauges is shown in **Figure 3.1**, and detailed locations of the stations used in analysis are presented in **Appendix G**. Details on the location and period of record of the gauge stations are provided in **Table 3.1**.

The distinction between ‘ocean tide’ and ‘estuarine tide’ stations depends largely on the issue of interest and becomes a subjective exercise. The transition from unimpeded ocean tides to topographically influenced tides in the nearshore and estuarine zones is not well defined due to the diverse morphology of estuary entrances and nearshore embayments. The water level monitoring stations within the NSW ocean tide network were selected to provide a best fit representation of ocean tidal characteristics.

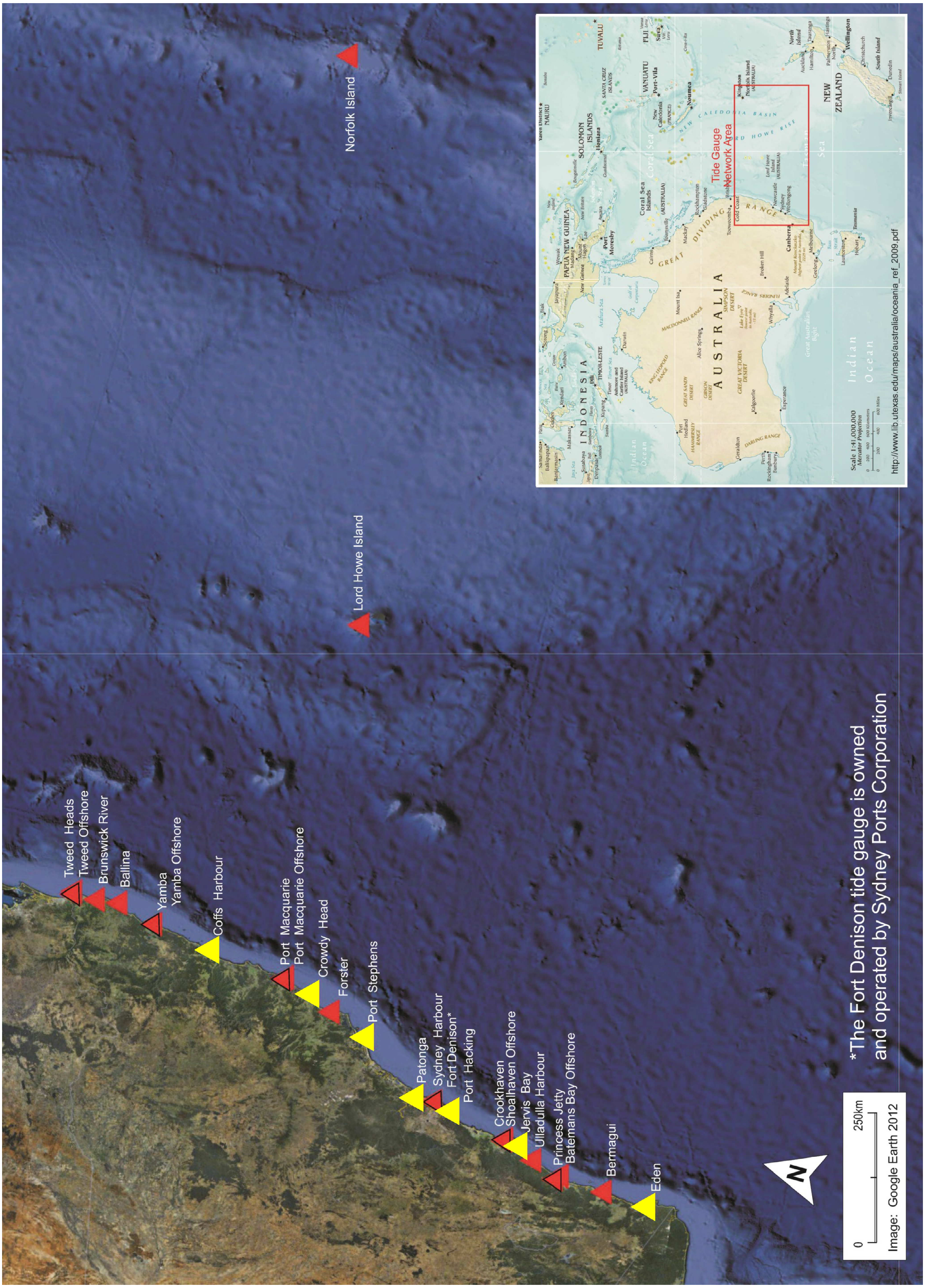
The ocean tide monitoring stations can be classified into two groups: offshore and onshore gauges. The offshore gauges are directly exposed to open ocean conditions and hence should be subject to a smaller range of non-astronomical tidal influences such as barometric and oceanic current effects, as they are located between 250 m and 3.5 km offshore, at depths of approximately 30 m. The locations of the onshore gauges are more variable, reflecting the variety of estuary entrances along the coast. Based on a consideration of the local bathymetry for each site, the locations of the gauges have been categorised into three different types:

1. **Open Ocean**. Pressure transducer located on the seabed in approximately 20–25 m water depth. Freshwater and bathymetric effects are considered negligible at these sites. Since there is no hard datum these gauges cannot be used for identifying variations longer than their deployment length of less than a year (such as sea level rise or ENSO cycles)
2. **Onshore Open Ocean or Open Bay**. Sites located on the open coast or large bay entrances with negligible influence by flood events and river flows. Seiching may pose a problem to harbour sites. Low pass filters have been applied at water level gauges with known seiching including Coffs Harbour, Crowdy Head and Ulladulla.
3. **Onshore River Entrance**. Sites located within a river entrance that may be subject to non-tidal freshwater events and changing entrance conditions.

The onshore open ocean or open bay stations are the sole station type within MHL’s ocean tide network considered suitable for extreme value analysis (other than Patonga which could also be classified as an open bay station), the underlying characteristic being that onshore open ocean or bay gauges remain largely unaffected by flood events and changing entrance conditions and hence provide the most reliable long-term extreme ocean water level trends for extreme value and water level anomaly analysis.

Two of the eleven onshore open ocean or open bay stations include East Australian Current influences and local effects – Norfolk Island and Lord Howe Island – and hence have been excluded from the extreme value analysis presented in this report. The Ulladulla, Sydney (Hunters Bay) and Port Hacking gauges have also been omitted from the extreme value analysis; Ulladulla due to its relatively short record length and the combination of two large events in that data that greatly broaden the confidence intervals of the extreme value fit, and Sydney (Hunters Bay) and Port Hacking, due to their proximity to the Fort Denison station. This results in seven suitable ocean water level stations comprising Coffs Harbour, Crowdy Head, Port Stephens, Patonga, Fort Denison, Jervis Bay and Eden marked in yellow in **Figure** 3.1.

This leaves the northern region of NSW, above Coffs Harbour, not well covered for extreme ocean water level analysis. The *North Coast Ocean Tide Site Scoping Study* (MHL2072 2013) confirmed a lack of suitable onshore open ocean or open bay (port or harbour) station locations north of Coffs Harbour.



*The Fort Denison tide gauge is owned and operated by Sydney Ports Corporation

Image: Google Earth 2012

http://www.lib.utexas.edu/maps/australia/oceania_ref_2009.pdf

OCEAN TIDE GAUGE NETWORK

NSW GOVERNMENT

Manly Hydraulics Laboratory

Report MHL2236
Figure
3.1

Drawing 2236-3.CDR

Table 3.1 Location descriptions and period of record of gauge stations

Site name	Period of data collected	Location description
Open Ocean		
Tweed Offshore	1982-1996	3.5 km offshore, between Tweed Heads and Fingal Head, 28 m depth.
Yamba Offshore	1987–2005	1.9 km offshore from Barri Point, 23 m depth.
Port Macquarie Offshore	1984-present	1.4 km offshore from Shelley Beach, 22 m depth.
Shoalhaven Offshore	2005-present	2 km offshore of Culburra Beach, in 25 m water depth.
Batemans Bay Offshore	2000-present	Between Black Rock and South Head, approx. 250 m offshore, 28 m depth.
Onshore Open Ocean or Open Bay Stations		
Norfolk Island	1994-present	On Kingston public jetty located on southern side of the island. Fringing reef surrounds the gauge and exposes the site to high surge and wave activity.
Lord Howe Island	1994-present	On public jetty off Lagoon Road. Gauge approx. 500 m from fringing reef on southern side of the island.
Coffs Harbour	1987-present	Boat harbour within Coffs Harbour, approx. 0.9 km from entrance to Coffs Harbour. Entrance to Coffs Harbour approx. 350 m wide, depths of 2-4 m in the boat harbour.
Crowdy Head	1986-present	Boat harbour on northern side of Crowdy Head.
Port Stephens	1985-present	Southern side of Port Stephens at Shoal Bay, approx. 0.5 km from entrance to port. Port entrance approx. 1.8 km wide, depths of 10-20 m at entrance, 3-5 m at the gauge.
Sydney	1987-present	Northern side of Middle Head in Hunters Bay, Sydney Harbour, approx. 3 km upstream of Sydney Harbour entrance. Sydney Harbour entrance approx. 2 km wide, depths of 20-30 m at entrance, depths of 3-7 m in Hunters Bay.
Fort Denison*	1914-present	North-eastern Side of Fort Denison, Sydney Harbour, approx. 7 km upstream of Sydney Harbour entrance. Sydney Harbour entrance approx. 2 km wide, depths of 20-30 m at entrance.
Port Hacking	1987-present	Located centrally approx. 1.5 km upstream on Port Hacking river. River entrance approx. 1 km wide and depths of 11-13 m at entrance.
Jervis Bay	1989-present	Deepwater harbour 6 km upstream of Jervis Bay entrance on southern side. Bay entrance approx. 5 km wide.
Ulladulla	2007-present	On southern end of jetty within Ulladulla Harbour. Approx. 350 m from entrance to harbour.
Eden	1986-present	Eden Wharf in Snug Cove, within Twofold Bay, approx. 5 km from entrance to Twofold Bay. Depths of 36-40 m at entrance to Twofold Bay, 4-8 m at Eden Wharf.
Onshore River Entrance Stations		
Tweed Heads	1987-present	Northern breakwater of Tweed River, approx. 0.6 km upstream of entrance. River entrance approx. 150 m wide, depth of 3-4 m to gauge. Shoal approx. 1-2 m deep 150 m on ocean side of breakwaters.
Brunswick Heads	1986-present	Southern training wall of Brunswick River, approx. 0.6 km upstream of entrance. River entrance approx. 60 m wide, depths of 1-3 m from entrance to gauge.
Ballina	1986-present	Southern breakwater of Richmond River, approx. 0.9 km upstream of entrance. River entrance approx. 300 m wide, depths of 2-8 m from entrance to gauge.
Yamba	1986-present	Southern breakwater of Clarence River, approx. 0.9 km upstream of entrance. River entrance approx. 400 m wide, depths of 3-10 m from entrance to gauge.
Port Macquarie	1986-present	Southern breakwater of Hastings River, approx. 0.7 km upstream of entrance. River entrance approx. 200 m wide, depths of 3-7 m from entrance to gauge.
Forster	1986-present	Approx. 0.35 km upstream of Cape Hawke Harbour entrance to Wallis Lake. Entrance approx. 120 m wide.
Patonga	1992-present	On jetty north side of Hawkesbury River, approx. 6 km upstream of the entrance (2 km wide).
Crookhaven Heads	1991-present	Southern side of Crookhaven River approx. 1 km from entrance and 100 m from local jetty. Entrance is approx. 750 m wide.
Princess Jetty	1985-present	On jetty south sides of Clyde River, 100 m downstream of the Pacific Highway bridge, ~ 300 m wide at the gauge.
Bermagui	1987-present	On jetty approx. 0.5 km from Bermagui River entrance (entrance approx. 100 m wide.)

🟨 = Station data used for Extreme Value Analysis.

* Data supplied by Sydney Ports Corporation.

3.2 Site instrumentation

Five distinct systems of data capture have historically been employed at the nearshore and offshore stations since continuous monitoring began: electromagnetic tide pole, solid state Floatwell, vented pressure sensor, radar and submersed water level pressure recorder. Each system functions as follows:

- Electromagnetic tide pole (EWS): the EWS gauge samples the water level continuously. The recorder samples at 1-second intervals and averages over 60 seconds to create a 1- or 15-minute data file.
- Vented pressure sensors: a vented pressure sensor determines pressure difference between the atmosphere and the water column above the sensor that is converted to water level. The recorder samples at 1-second intervals and averages over 60 seconds to create a 15-minute data file. These data are then transferred to MHL as for the EWS. These units are mostly deployed as backup systems to primary EWS units.
- Solid state Floatwell: the level is sensed by a float connected to a shaft encoder, which is read and stored every 15 minutes.
- Submersed water level recorder: the water level is determined by an absolute pressure sensor. Atmospheric pressure is obtained from nearby barometer stations maintained by MHL and subtracted from the absolute pressure to give pressure associated with hydrostatic head. The recorder stores data internally each hour, integrating data over a 40-second period.
- Radar: The sensor is located directly above the surface to be measured with radar measuring the distance to the water surface. The beam is divergent so the water surface is effectively averaged spatially over a circular area of 1-2 m^2. The radar is extremely stable over a range of operating conditions and is not prone to drift, so is extremely accurate and reliable for tidal measurement. The recorder uses a 60-sample average 30 seconds either side of each minute.

Averaging high frequency samples over a certain time period, e.g. 1-second sampling over 60–120 seconds, limits the likelihood of surface waves affecting water levels. Generally, these stations are formally logged and quality checked at a 15-minute sample rate. While most stations have been upgraded to log at 1 minute, this is not formally supported or quality coded so the analysis in this report is limited to 15-minute data.

The submerged offshore pressure sensors have historically been logged at 1-hour intervals, and in 2012 were upgraded to 5-minute sampling intervals. This tends to be noisy data so for consistency in the analysis, and since the 1-hour sampling represents the bulk of the data, only the 1-hour data has been analysed. Values are the average of 40 samples at 1-second intervals.

The instrumentation is rarely constant over time, and is upgraded with new and better equipment as it becomes available, allowing for improved accuracy, reliability, maintainability and ease of installation. The history of the changes to each site has been captured in report MHL2179 *Tide Gauge Histories*.

Details of the current recording instrumentation for each site are provided in **Table 3.2**.

Table 3.2 MHL current logging and sensing system

Station	Site classification[1]	Primary loggers	Secondary loggers	Primary sensors	Secondary sensors	Station	
						Sampling	Logging
Tweed Heads	OR	CR1000		Radar	Vented pressure	120 samples averaged 1 minute either side of the quarter hour and 60 samples averaged 30 seconds either side of each minute Lord Howe, Patonga and Princess Jetty stations logging at 1 second to onsite data storage card	15 minutes on the quarter hour and 1 minute on the minute
Brunswick Heads	OR	CR800	-	Vented pressure	Vented pressure		
Ballina Breakwall	OR	CR800	-	Vented pressure	Vented pressure		
Yamba	OR	CR800	-	Vented pressure	Vented pressure		
Coffs Harbour	OB	CR800		Radar	Vented pressure		
Port Macquarie	OR	CR800	-	Radar	Vented pressure		
Crowdy Head[3]	OB	CR800	-	Radar	Vented pressure		
Forster	OR	CR800	-	Vented pressure	Vented pressure		
Port Stephens	OB	CR1000	-	Radar	Vented pressure		
Patonga	OB	CR800		Radar	Vented pressure		
Sydney	OB	CR800		Radar	n/a		
Sydney Backup	OB	CR800		Vented pressure	Vented pressure		
Port Hacking	OB	CR1000	MetOcean	Radar	Vented pressure		
Crookhaven	OR	CR800	-	Vented pressure	Vented pressure		
Jervis Bay	OB	CR800	-	Radar	Vented pressure		
Ulladulla	OB	CR800	-	Vented pressure	Vented pressure		
Princess Jetty	OR	CR800		Radar	Vented pressure		
Bermagui	OR	CR800	-	Vented pressure	Vented pressure		

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Station	Site classification[1]	Primary loggers	Secondary loggers	Primary sensors	Secondary sensors	Station	
						Sampling	Logging
Eden	OB	CR800		Radar	Vented pressure		
Norfolk Island	OO	CR800	-	Floatwell	Vented pressure		
Lord Howe Island	OO	CR1000	-	Radar	Vented pressure		
Tweed Heads[2]	O	WLR7	-	Submersible Paroscientific pressure sensor and RBR logger	Aanderaa submersible pressure	Integrated over 40 seconds	RBR 5 minutes Aanderaa 60 minutes
Port Macquarie[2]	O	WLR7	-				
Shoalhaven[2]	O	WLR7	-				
Batemans Bay[2]	O	WLR7	-				

[1] Classification: O = Offshore Open Ocean, OO = Onshore Open Ocean, OR = Onshore River entrance, OB = Onshore Bay or Port

[2] Offshore tidal site

The Fort Denison tide gauge is owned and operated by Sydney Ports Authority. Data is available earlier than the listed 1914, but is known to be unreliable prior to the installation of a Harrison chart recorder. The current instrumentation at the site is a Searanger sonic water level sensor.

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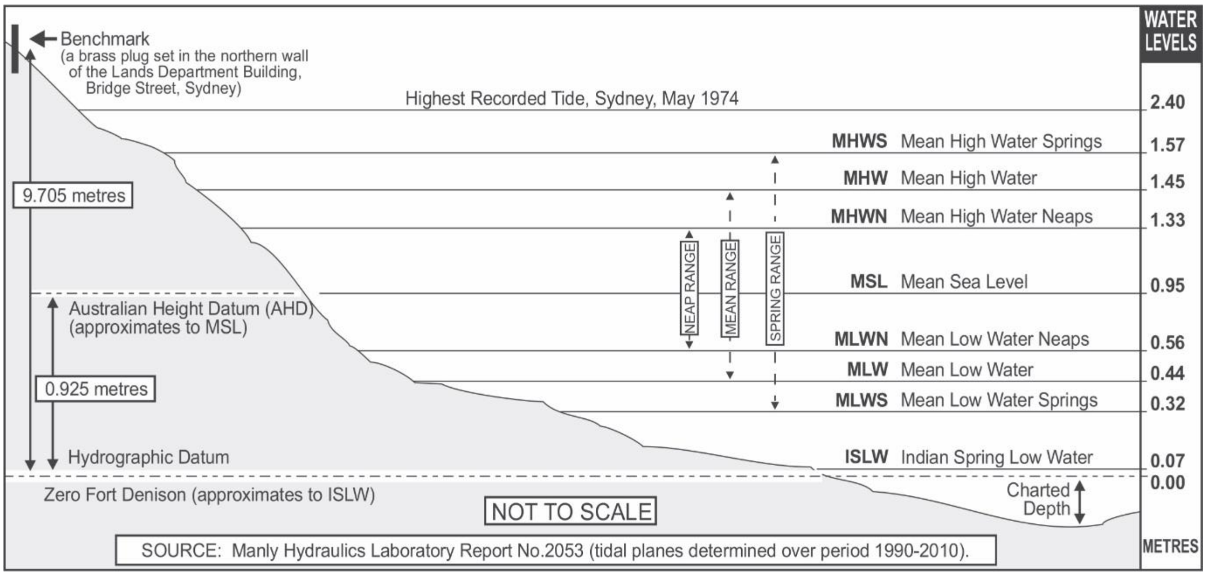
3.3 Australian Height Datum adjustment

The Australian Height Datum (AHD) is a geodetic datum for altitude measurement in Australia. According to Geoscience Australia, in 1971 the mean sea level for 1966–1968 was assigned a value of zero on the Australian Height Datum for 30 tide gauges around the coast of the Australian continent. The resulting datum surface has been termed the Australian Height Datum and was adopted by the National Mapping Council as the datum to which all vertical control for mapping is to be referred. An example of the calculation of AHD to local datum in Sydney is provided in **Figure 3.2**. The relationship between the MSL and AHD between 1990-2016 along the NSW coastline is illustrated in **Figure 3.3**. It should be noted that this relationship is not static over this period but varies with interdecadal and longer-term sea level changes.

Each ocean tide level gauge is recorded in the local port datum which generally equates to Indian springs low water (ISLW). An indicative adjustment of each station datum level to the local AHD is shown in **Table 3.3** and illustrated in **Figure 3.4**. These adjustments were calculated circa 1990 by Roger Harvey from NSW Public Works, using tidal harmonic analysis over a tidal epoch. Offshore Aanderaa stations are not related to a datum, but provide valuable information on astronomical constituents and anomalies.



SOURCE: Manly Hydraulics Laboratory Report No.2053 (tidal planes determined over period 1990-2010).

Figure 3.2 Sydney calculation of AHD to local datum

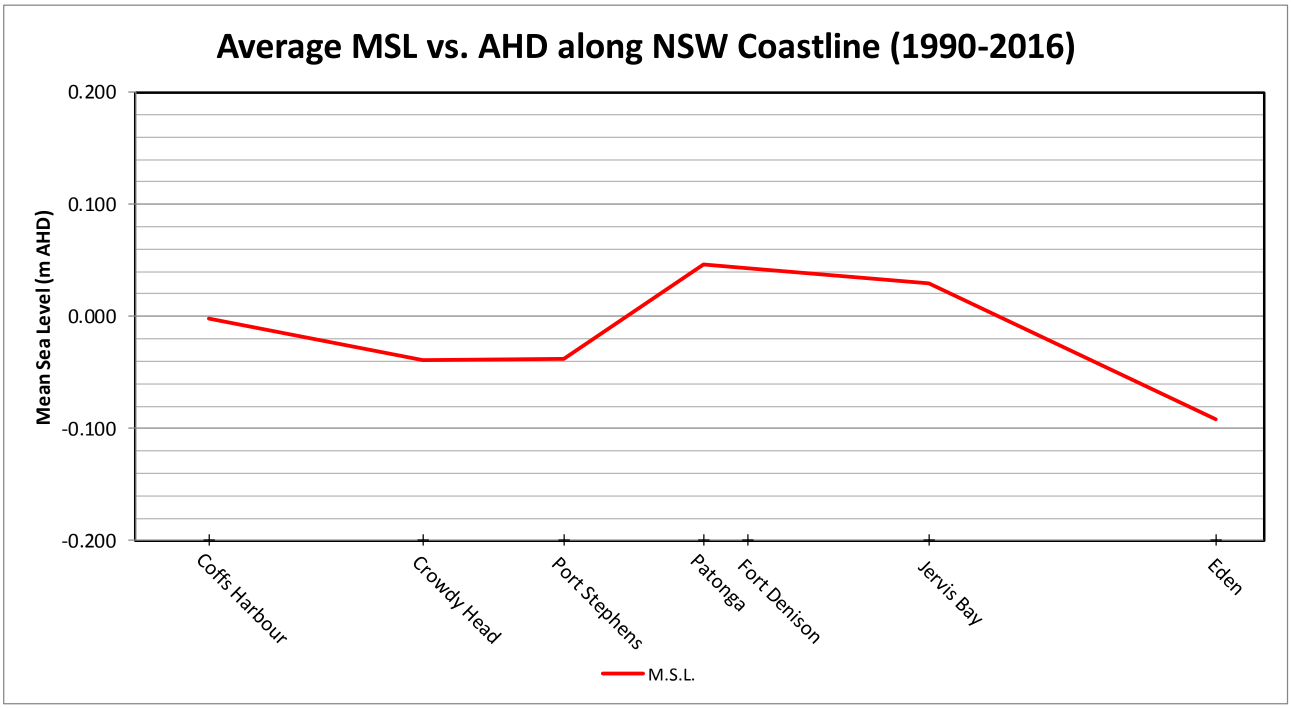


Figure 3.3 MSL vs. AHD relationship along the NSW coastline

Table 3.3 Summary of adjustment to local AHD

Station	Station datum	Adjustment (AHD–local)	MSL (1995–2014 Epoch to AHD)
Tweed Heads	Tweed River Hydro Datum	–0.893	0.04
Tweed Heads Offshore	Mean Sea Level	NA	NA
Brunswick Heads	Brunswick River Flood Mitigation Datum	–0.046	0.02
Ballina	Low Water Ordinary Spring Tide	–0.860	0.03
Yamba	Iluka Port Datum	–0.895	0.05
Yamba Offshore	Mean Sea Level	NA	NA
Lord Howe Island	Lord Howe Island Hydro Datum	NA	NA
Norfolk Island	Norfolk Island Tidal Datum	NA	NA
Coffs Harbour	Coffs Port Datum	–0.882	0.02
Port Macquarie	Australian Height Datum	0.000	0.02
Port Macquarie Offshore	Mean Sea Level	NA	NA
Crowdy Head	Crowdy Head Datum	–0.911	-0.03
Forster	Forster Hydro Datum	–1.061	-0.03
Port Stephens	Port Stephens Hydro Datum	–0.944	-0.02
Patonga	Australian Height Datum	0.000	0.06
Sydney	Zero Camp Cove	–0.925	0.03
Fort Denison	Zero Fort Denison Tide Gauge	–0.925	0.04
Port Hacking	Indian Spring Low Water	–0.925	0.08
Crookhaven Heads	Australian Height Datum	0.000	0.03
Jervis Bay	Chart Datum	–1.070	0.02
Ulladulla	Australian Height Datum	0.000	0.04
Princess Jetty	Australian Height Datum	0.000	0.06
Batemans Bay Offshore	Mean Sea Level	NA	NA
Bermagui	Bermagui Local Hydro Datum	–0.714	-0.02
Eden Boat Harbour	Twofold bay Hydro Datum	–0.924	-0.08

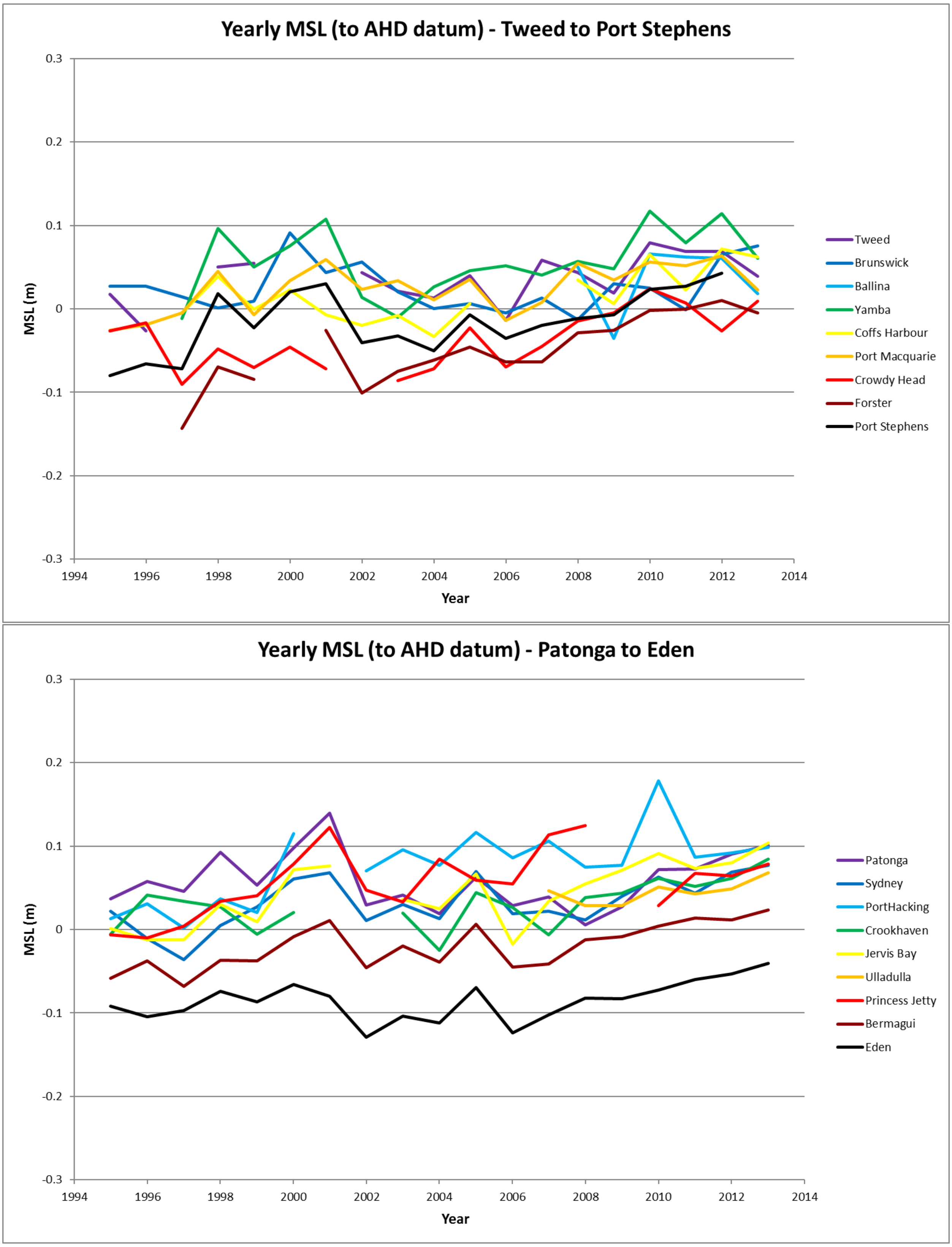


Figure 3.4 Yearly MSL values to AHD datum along the NSW coastline over time

3.4 Land level changes

All water level recordings used in this report are relative to the local land level. No adjustment has been made to account for changes to land level due to difficulties in obtaining accurate information on land movement. Land levels may be influenced by a range of processes including tectonic, Glacial Isostatic Adjustment (GIA) and gravitational adjustments. Rates of GIA for NSW are available at http://www.pol.ac.uk/psmsl/_landmove.html. The lack of comprehensive data for NSW has precluded any definitive adjustment to sea level, so all analysis in this report is relative to local land level.

4. Ocean water level analysis methods

4.1 Harmonic analysis and residuals

Details of MHL's tidal analysis methods and techniques are provided in MHL2156 *MHL Tidal Methodology Review* (in draft). Summary information about the method is provided here. Harmonic analysis remains the accepted method of resolving the astronomical tide from the tidal record.

4.1.1 Harmonic analysis

Harmonic analysis is the process of measuring or calculating the relative amplitudes and phases of the sinusoidal components present in a given wave form. The frequencies of the harmonic constituents are based on astronomical influences – movements of the sun and moon relative to earth. The regularity of astronomical motion implies the presence of periodicities in water level records, and the determination of these is the primary task of an analysis. A series of measurements of the tidal displacements at a given point can usually be fitted by a sum of harmonics, resulting in a number of partial tides or constituents with set tidal frequencies (MHL, 1995). Each tidal constituent has a sinusoidal wave form, as provided by the following equation:

$$h_k = a_k \cos\left(2\pi f_k t - G_k\right) \tag{4.1}$$

where	a_k	amplitude of the *k*-th tidal constituent
	f_k	frequency of the *k*-th tidal constituent
	G_k	G-phase is the phase-lag of the local tidal constituents compared to the Equilibrium Tide (i.e. its phase at Greenwich, England)
	t	time

As mentioned, the recorded tide can be affected by a variety of non-astronomical influences due to meteorological, hydrological and oceanographic effects. For riverine and estuarine sites, flooding events may have an impact on the analysis. For the stations analysed here, the freshwater influence is considered to be relatively small, and flood events have not been removed from the data. They will, however, affect the results, and some river entrance stations have large events associated with flooding. While the tide climate at river entrance stations can be considered representative of the ocean, users should be aware that extreme events at these stations are not.

Historically, MHL used the Godin tidal height analysis and prediction routines developed by Foreman (1979) to generate the amplitudes and phases of a series of harmonic constituents. This program was updated by Foreman in 2008 with the Versatile Tide Analysis package and provides improvements to the method of nodal corrections and inference, and the addition of detailed post-run analytics. This has been incorporated into MHL's standard analysis method and has been used for the analysis in this report. Details of the package and comparison with the earlier program can found in MHL2156 *Tidal Methodology Review* (in draft).

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Typically, the Foreman program divides the tide into the 45 astronomical constituents and 24 shallow water constituents for a 366-day tidal record. A complete list of the harmonic constituents generated by the programme is provided in **Table A1, Appendix A**, together with the frequency and associated planetary derivations of the constituents. Analysis is performed on one-year blocks of data rather than across the whole dataset at once; this allows variations in ocean water levels that may occur on inter-annual scales to not affect the tidal residual. The residual is then just a measure of the meteorological and oceanographic effects over hours to months, rather than climate variability over years.

4.1.2 Tidal predictions and anomalies

The use of the constituents $(M, S, N, K)_2$, $(K, O, P)_1$ will generally be sufficient to predict the astronomical tide signal to about 90% at the tide gauges exposed to open ocean conditions. The difference between the astronomical tide signal and the water level measurements is generally attributable to the effects of local meteorological conditions.

While seven principle harmonic constituents are generally sufficient for predicting tidal signals in open ocean conditions, the Foreman programme used by MHL to calculate tidal predictions utilises all 69 constituents generated by the programme when predicting tidal levels at a particular site (MHL, 1995).

The predictions were generated using the actual year of data to extract the harmonic constituents, i.e. 2007 tidal data was used to extract harmonic constituents to generate tidal predictions for 2007. Early investigations in this project showed that using constituents developed from previous years resulted in errors in the residual (the results are not presented here). Tidal anomalies were calculated using the formula:

$$\textit{Observed Water Level} - \textit{Predicted Water Level} = \textit{Residual Water Level} \qquad (4.2)$$

It is important to note the difference in residual due to the analysis in yearly parts and that by analysis of the entire dataset. The difference is caused by seemingly random long-term variation in water levels (due to changes in climate and ocean circulation). In choosing to analyse in parts, the long-term variability is captured in a changing mean sea level, and anomalies are only due to short processes (less than a year). By choosing to analyse a full record, the anomaly incorporates the annual variability and the shorter meteorological effects – leading to extended periods of high or low anomalies. Neither approach is incorrect, but captures the processes in different ways so must be considered when interpreting the results.

Extraction of the residual is an imperfect process since harmonic analysis assumes that the tide signal remains stationary. This is rarely the case and is more problematic as the tide travels upstream and is increasingly affected by bathymetry that may change over time. When slight changes to the tide occur within the analysis period, some tidal energy will be passed to the residual. This will clearly be more problematic for estuarine sites, but is also a consideration in both bay/harbour and offshore sites. This will have some impact on all results in this report relating to the residual. Any derived anomaly with semi-diurnal frequencies are indicative of phase errors in the anomaly derivation process.

4.1.3 Residual error

To determine whether a predicted tide provides a good representation of the observed water level record, the difference between the two, or the tidal residual, is calculated. The residual error is expressed in terms of the Root Mean Square (RMS) of the hourly difference between the observed and predicted tides (tidal residual) and is calculated as follows:

$$X_{RMS} = \sqrt{\left(\frac{\sum x_i^2}{n}\right)} \tag{4.3}$$

where x_i difference between observed tide and predicted tide at time *i*

n number of tidal records

The RMS error is a measure of how accurately the harmonic analysis models the measured tide. This should not be confused with the accuracy of the measurement. An RMS error of less than 0.12 m is considered acceptable for stations with mean ranges approximating NSW coastal ocean tides (MHL, 1995). For stations with a much smaller mean range than coastal ocean tides, non-astronomical water level variations account for a significantly greater proportion of the variability in the observed water level, resulting in potentially larger RMS residual errors in comparison with stations with mean coastal ocean range (MHL, 2003).

4.2 Frequency distribution analysis

The frequency distribution of measured and anomaly data was conducted, which provides valuable information about the primary mode of the measured and residual signals. It is based on interval classes of 15-minute water levels (and 60-minute for Fort Denison) recorded since the inception of the station. This method was based on the flood frequency method described in Pilgrim & Doran (1999).

The interval method has been used to categorise recorded water levels from a station into pre-defined classes (of 0.1 m bins) to then calculate their frequency of occurrence. The number of data points falling into each interval for that range of data was determined. The number of points in each interval is then divided by the total number of points, which gives the frequency of occurrence of each interval for the data period available. The percentage exceedance is then calculated by counting the number of times the water level has exceeded that particular 0.1 m interval and then dividing this by the total number of exceedance values.

Frequency distributions for these stations and all other tidal stations in the OEH network are provided in MHL2100 *OEH NSW Water Level Frequency Distribution Analysis.* Further information on the methodology is detailed there.

Users should be aware that the estuarine stations may be affected by changing entrance conditions and the residual results may include some tidal energy. The frequency distribution has been conducted on measured data, and no detrending has been conducted prior to analysis, even for Fort Denison.

4.3 Tidal planes analysis

A commonly used approximation of the tidal planes is determined from the major tidal constituents derived by harmonic analysis. Tidal planes and ranges were calculated for each year of harmonically analysed data for each station. The major constituents used and the equations of the tidal planes are given in **Tables 4.1** and **4.2**.

The mean sea level component of water level (Z0) is also derived from the harmonic analysis and is used in the calculation of the tidal planes. Z0 is approximately the average of all data points, but is also included in the analysis along with the constituents, so provides the true mean sea level (over the period of analysis), where the average of points may provide bias in the case of systematic data loss. Refer to MHL2156 (2012 in draft) for more detail.

Table 4.1 Major constituents used in tidal plane calculations

Constituent	Origin	Period (hours)	Angular speed (minutes/degrees)
Z0 (mean sea level)		-	-
M2 (semi-diurnal)	Principal lunar	12.42	2.07
S_2 (semi-diurnal)	Principal solar	12.00	2.00
K_1 (diurnal)	P. lunar/P. solar	23.93	3.99
O_1 (diurnal)	Principal lunar	25.82	4.30
M_{sf} (fortnightly)	Lunisolar synodic	354.37	59.06

Table 4.2 Calculation of tidal planes and ranges

Tidal plane		Derivation
High High Water Solstices Springs	**HHWSS**	$= Z_0 + M_2 + S_2 + 1.4 (K_1 + O_1)$
Mean High Water Springs	**MHWS**	$= Z_0 + (M_2 + S_2)$
Mean High Water	**MHW**	$= Z_0 + M_2$
Mean High Water Neaps	**MHWN**	$= Z_0 + (M_2 - S_2)$
Mean Sea Level	**MSL**	$= Z_0$
Mean Low Water Neaps	**MLWN**	$= Z_0 - (M_2 - S_2)$
Mean Low Water	**MLW**	$= Z_0 - M_2$
Mean Low Water Springs	**MLWS**	$= Z_0 - (M_2 + S_2)$
Indian Spring Low Water	**ISLW**	$= Z_0 - (M_2 + S_2 + K_1 + O_1)$
Tidal Range		**Derivation**
Mean Neap Range	**MNR**	= MHWN–MLWN
Mean Range	**MR**	= MHW–MLW
Mean Spring Range	**MSR**	= MHWS–MLWS
Range	**R**	= HHWSS–ISLW

4.4 Joint probability analysis

Joint probability analysis is a technique that has been applied in the past to the annual recurrence interval problem for water levels. In this method, the tides and residuals are separated using harmonic analysis, and the probability distributions of each determined. These can then be recombined to provide an ARI for each level.

It is very difficult to entirely remove the tide signal from the residual, so there is generally a small tidal component in at least part of the residual. This comes with a larger uncertainty. The prerequisite assumption of joint probability analysis that the two signals are independent is then invalidated. It is reasonable to assume that tide and anomaly signals are independent, but the limitations of harmonic analysis provide an imperfect separation of signals. In practice, this means that the residual distribution is higher than it should be, and the method overestimates the water level for a given recurrence interval.

4.5 Extreme value analysis

Determining water levels across the NSW coast requires a more in-depth analysis than looking at water variability around the central mode. Extreme values are of particular interest as they are the most damaging, and are the most difficult to predict.

Extreme value analysis was traditionally done using a block maxima approach, such as curve fitting using a suitable function such as the Weibull, Gumbel, Generalised Extreme Value (GEV) or others. However, this approach is wasteful if the extremes are not evenly distributed through the record (Coles, 2001). This is especially true for water levels, where all forcing mechanisms show strong inter-annual variation (though not necessarily correlated). Tides vary over an 18.6-year cycle, and all drivers of tidal anomalies vary with climate variability. The result of this is clusters of extremes around spring tides and years of increased storminess.

To maximise the use of all recorded extremes, peak-over-threshold methods include all events over a suitably chosen threshold generally set at two standard deviations above the mean which are at least six days apart. This is then fitted to the Generalised Pareto (GP) distribution with cumulative distribution:

$$F(x) = exp\left\{-\left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \qquad (4.4)$$

for some $\mu,\sigma > 0$ and ξ (Coles, 2001)

When this approach is applied to water surface levels, it is improbable that these two threshold level setting assumptions will hold during an event during a spring tide, for example, as peaks can be counted twice or combined as one. Separating each anomaly into their individual drivers for each station is one method of improvement, however, this requires significant manual work well beyond the scope of the present study, and separating tidal anomalies into their generation mechanism is also problematic, for example, there may be concurrent drivers such as a shelf wave with an East Coast Low (**Appendix E**).

The other alternative approach is given in **Appendix E** (Callaghan et al., 2017) where the tidal anomaly is estimated and its events are modelled before being reintegrated with the deterministic astronomical tide. This is known as the maximum operator gradient approach

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(‘max-gradient-approach’). This approach selects events when the maximum tidal anomaly function obtained by finding the maximum in a moving window of δ on tidal anomalies is constant for a considerable amount of that window size ($a \times \delta$ and $0 < a < 1$). This approach is implemented by determining when

$$\frac{\partial}{\partial t} \max\left\{\eta\left(t \in \left[t - \tfrac{\delta}{2}; t + \tfrac{\delta}{2}\right]\right)\right\} \tag{4.5}$$

is continuously zero for a duration of at least $a \times \delta$ (Callaghan, 2008).

4.6 Detrending considerations

Extreme ocean water level analysis can be affected by long-term climate cycles such as Interdecadal Pacific Oscillation (IPO) which can span 20–60 years. Other longer cycles may compound this. For the purpose of extreme value analysis the long-term trend is assumed to be zero. Ocean port and bay stations simply do not have the record length for this to be applied. However, Fort Denison covers such a long record that extremes in the record may not be well represented in the analysis due to the longer climate variability cycles and sea level rise trends. Linearly detrending the record prior to analysis can, for example, artificially raise extremes from the 1950s. In the analysis of Fort Denison, a rolling 30-year average from 1985–2015 is applied to remove signals associated with the longer climate variability cycles and sea level rise.

This report compares both detrended and non-detrended data sets in water level and tidal anomaly ranking for Fort Denison in **Appendix B**, extreme value determination in **Appendix C** and **Appendix D** and in a comparison of all extreme value methods in **Appendix E**.

It can be observed that while the detrending slightly affects the water level values and ranking, it has only very minor impact on the recorded anomaly. Detrending allows to differentiate the non-stationary effects from the sea level changes and reduces the range of the confidence interval.

4.7 Uncertainty analysis

When completing such extreme value analysis, it is essential to understand the uncertainties that can occur at each step of the process. Callaghan et al. (2017) provide extensive information on the possible extreme still water levels analysis methods and the associated errors. Water level along the NSW coastline depends on a number of factors such as deterministic astronomical tide, global sea level changes and stochastic processes including local and ocean seiches, floods, Rossby waves, tsunamis, barometric pressures, coastally trapped waves, winds, oceans currents and local land movements. Fitting of the data can be conducted by fitting to the water levels directly or by separating the dominant deterministic process of the tide from the stochastic processes. Both methods generate some uncertainties. The first method is likely to underestimate the results by missing significant stochastic events occurring at low tide. The second method introduces uncertainties related to the separation of the deterministic tide.

The following sections detail the main sources of uncertainty and seek to provide an estimation of the error.

4.7.1 Statistical method uncertainty

A number of statistical methods were applied and the resulting extreme water levels were compared (Callaghan et al., 2017). The analysed methods include:

- block maxima between two months and two years with the generalised extreme value distribution
- peak-over-threshold (POT) method using water levels and GP distribution
- POT using anomalies and GP distribution with simulation to recombined with tide
- POT using water levels and GP distribution and including joint probability between events.

Comparing the results of the four methods shows a difference in water levels in the order of approximately 0.1 m for the 100-year ARI level. This is consistent with the 100-year 95% confidence interval and hence this uncertainty is as significant as the sampling error.

4.7.2 Non-stationary uncertainty

Non-stationary or climate indices uncertainties were estimated by breaking up the Fort Denison measurements into 18.61-year, half overlapping periods (lunar nodal tidal period) (**Appendix E**). This provided nine distribution fits that presented a variation in the order of 0.25 m. This analysis considered both *as measured* highlighting the impact of the sea level rise and non-stationary changes on the distributions and *detrended* (as described in **Section 4.6**) isolating the non-stationary changes. This has a larger magnitude than the sampling magnitude uncertainties which makes the extrapolation out to 3–5 times the record length invalid. The 95% confidence range covering all individual ranges for the 100-year ARI is 91 cm.

4.7.3 Parameter estimation methods uncertainty

A number of distribution fitting methods are available. The most common method used is the maximum likelihood method. The L-moments method was therefore applied as a comparison (Callaghan et al., 2017). Results of the comparison showed a difference in the order of 0.02 m which is much less than the other uncertainties previously described.

4.7.4 Measurement method uncertainty

Measurement methods such as frequency of measurement and averaging techniques will influence the values being recorded to the order of 0.2 m during conditions such as large wave and wind. It is important to understand the impact of these influences and the context of what the recorded levels are being used for. It is suggested that further investigation be undertaken to gain an improved understanding of this uncertainty.

5. Results and discussion

5.1 Extreme value analysis

5.1.1 Extreme ocean water level

The Fort Denison tide station was analysed to determine the magnitude of uncertainty from analysis methods and other climatic variability such as El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). For method uncertainties, block maxima using generalised extreme value distribution as well as peak-over-threshold and max-gradient approaches combined with Generalised Pareto were compared and found to agree within ± 0.1 m. For analysis method and climatic variability combined, uncertainty of 0.25 m has been estimated at the 100-year return period (**Appendix E**).

Following the analysis of the Fort Denison tide station, the Generalised Pareto model was chosen for presentation of the extreme ocean water levels. **Table 5.1** presents the 20-year and 100-year ARI levels obtained using the Generalised Pareto model fit at each station. These analyses provide a range of analytical results for each station that can be used for coastal management and design purposes. Extreme value analysis ocean water levels should be used with caution, noting that extreme values in the future may not be forecast from the historical records. That is, the figures are representative of the current and historical conditions, not necessarily future conditions.

Table 5.1 20-year and 100-year ARI extreme water level along the NSW coastline

Station	20-year ARI levels using GP (m AHD)			100-year ARI water level using GP (m AHD)		
	Model	Lower limit	Upper limit	Model	Lower limit	Upper limit
Coffs Harbour*	1.43	1.39	1.59	1.49	1.42	1.86
Crowdy Head*	1.38	1.35	1.46	1.43	1.39	1.56
Port Stephens	1.31	1.27	1.39	1.36	1.31	1.50
Patonga	1.39	1.35	1.48	1.43	1.39	1.59
Fort Denison	1.35	1.32	1.39	1.42	1.38	1.53
Jervis Bay	1.32	1.29	1.40	1.36	1.32	1.50
Eden	1.25	1.21	1.35	1.30	1.25	1.52

GP = Generalised Pareto model fit * low pass filter applied to known seiche-affected sites

Figure 5.1 shows a summary of the extreme value analysis of ocean water levels for the ocean port and bay sites in NSW for 20-year and 100-year General Pareto model fits with accompanying 95% confidence intervals. The General Pareto including joint probability between events using Ferro and Seagers (2003) model for both 20-year and 100-year return interval are fitted for comparison. This shows an approximate 0.2 m decreasing trend of extreme ocean water levels from north to south, with non-uniformities around Port Stephens and Patonga. Confidence intervals vary within 0.2 m for the 20-year ARI extreme ocean water levels and within 0.5 m for the 100-year ARI levels. A reduction in confidence interval is observed at Fort Denison, associated with the longer record length.

The onshore open ocean and open bay stations are currently the most effective option to record water level. Low pass filters have been applied at water level gauges with known to be affected by seiching. It was found that no such station is available north of Coffs Harbour and the northern shore of NSW is, therefore, not as well covered as the southern part of the coastline. Details of the recurrence of extreme ocean water levels as well as extreme tidal anomalies for NSW including probability and cumulative distributions for each station are presented in **Appendix C**.

The present findings are in good agreement to former extreme value analysis studies (MHL621 1992 and MHL1881 2011) indicating similar overall trends despite the change in recording equipment, sampling regime, averaging methods. Each station also recorded an additional 5-6 years of data since the last study. Extreme water levels at Fort Denison for the present study are slightly lower (in the order of up to approximately 0.05 m) than previous results due to use of a longer dataset with no new levels in the top five records (being the events that influence the tail of the fitted curve the most).

Results from the present study estimate the Fort Denison 100-year ARI to be 1.42 m. This indicates that the highest recorded water level at Fort Denison of 1.48 m AHD on 25 May 1974, based on more than 100 years of records, could be characterised by an ARI slightly greater than 100 years, as might be expected. It should be noted that the ARI for the 1974 event could range from between 50 years to greater than 200 years based on the confidence limits of the extreme value analysis. The inclusion of the Fort Denison tide gauge provided further depth to the analysis and context for longer-term variability on the NSW coast.

Comparison of extreme value analysis results with detrending are presented in **Appendix C**. Use of detrending techniques to allow separation of the non-stationary effects from long-term sea level changes was shown to reduce the confidence interval range. This detrending of the Fort Denison record demonstrated only a small difference in extreme water levels and very minor effects on the tidal residuals. **Appendix C** also contains comparison plots for block maxima and peaks-over-threshold methods for actual and detrended extreme values.

In addition to analysis methods and climatic variability, sources of uncertainty may also include the parameter estimation for fitting of the distribution and the measurement method applied, including sampling frequency and averaging techniques. The former has a minimal influence in the order of 0.02 m. The latter, however, can influence the records in the order of 0.2 m during specific local conditions such as large waves or wind.

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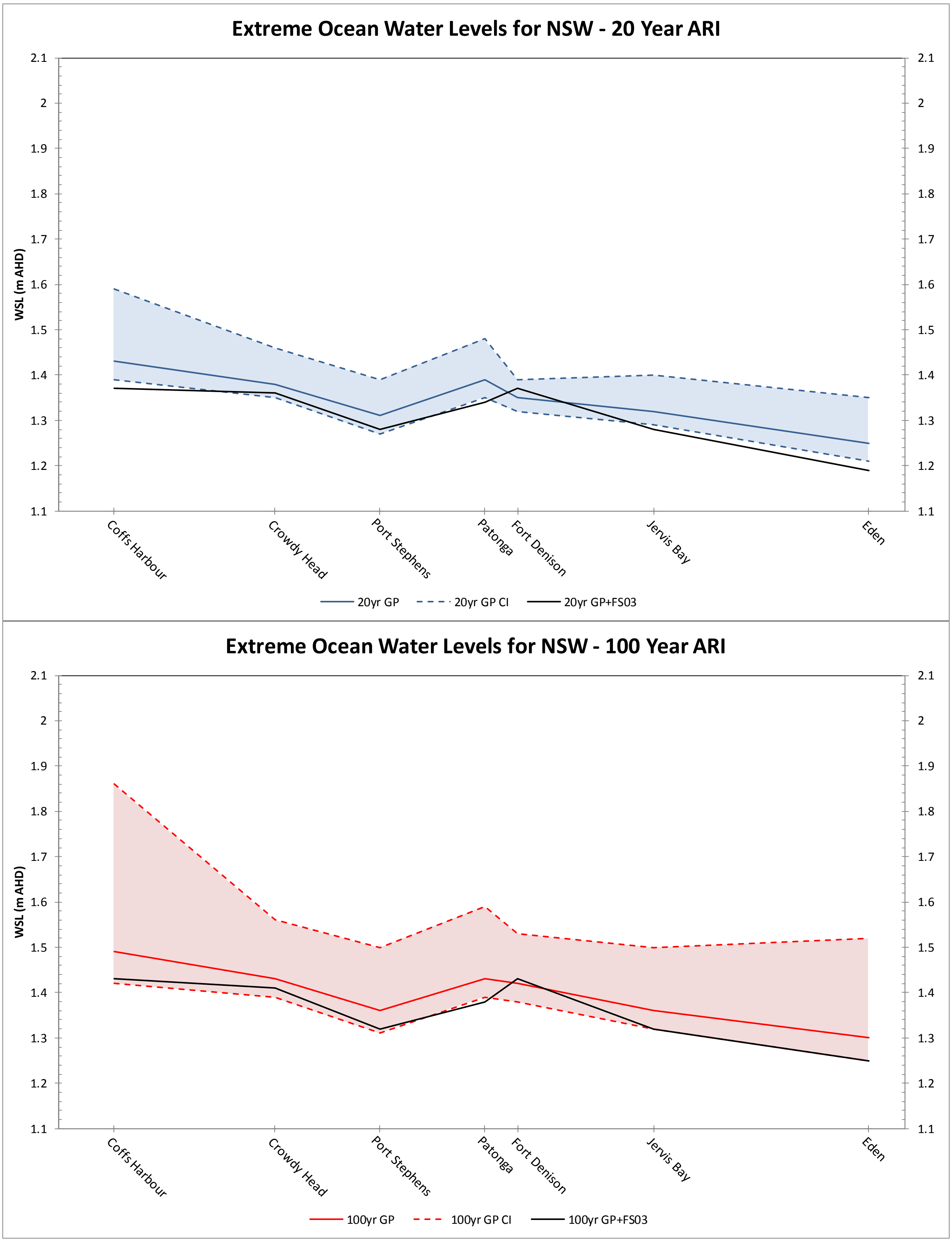


Figure 5.1 Extreme water levels plots for NSW coastline with 20-year and 100-year GP model with upper and lower confidence intervals along with the General Pareto Ferro and Seagers (2003) model fit (GP+FS03)

A comparison of the extreme level fits of Fort Denison (long dataset) and Ulladulla (short dataset) exemplify the need for long datasets to provide a reasonable fit. **Figure 5.2** is Fort Denison with over 100 years of data to model and fit a best possible trend line for the 100-year return with tight confidence intervals. **Figure 5.3** shows the extreme level fit with only 10 years of data. As there are two events that lie outside the trendline in such a small data set, the confidence interval skews outwards and is indicative of a low confidence fit in the model. This comparison highlights the need for continual data capture by MHL on all coastal ports and bays to continually improve NSW extreme level analysis for the entire coastline.

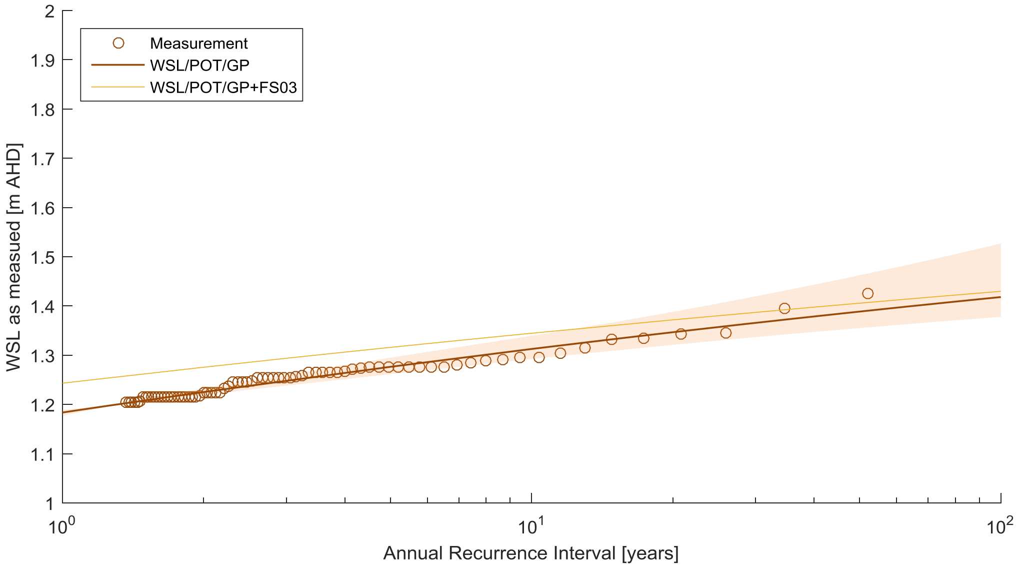


Figure 5.2 Exceedance water level for Fort Denison

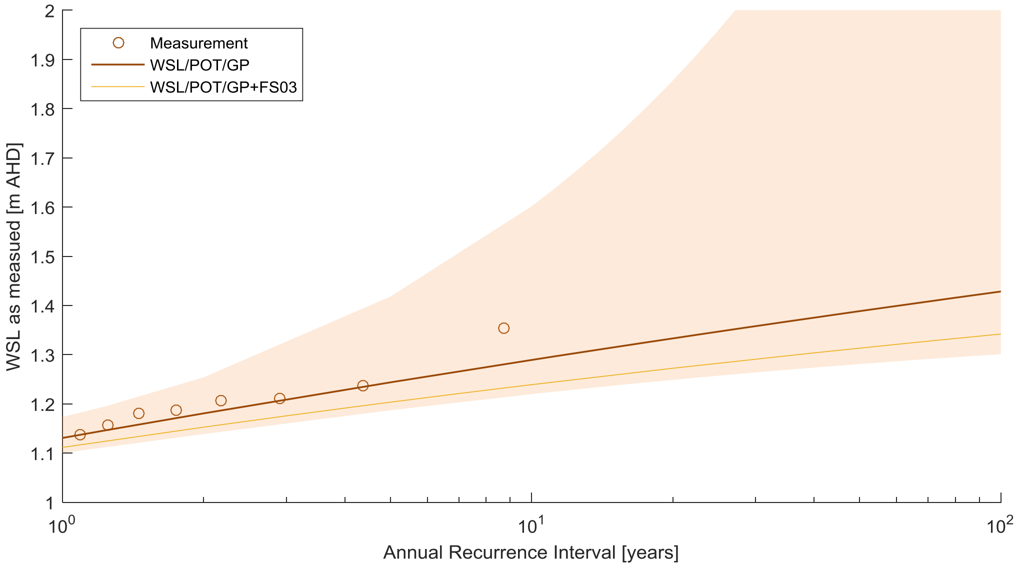


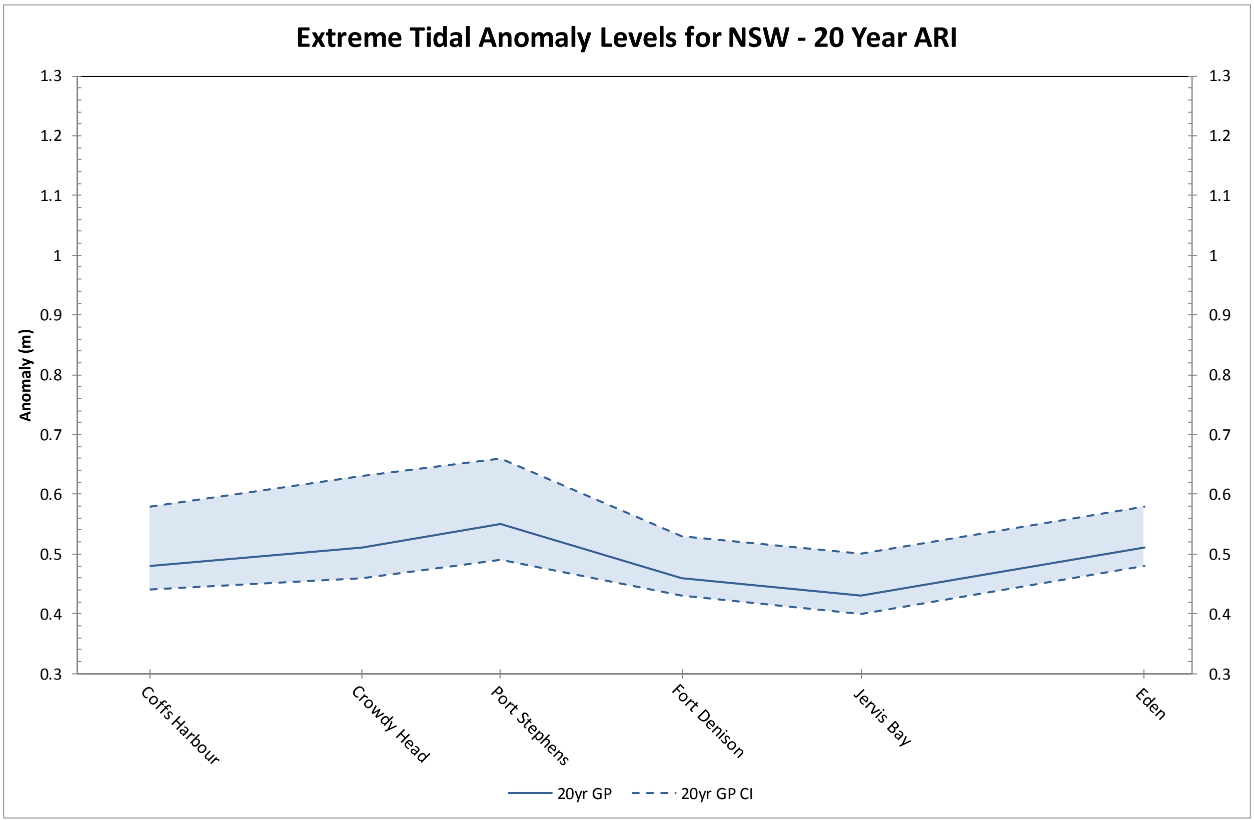
Figure 5.3 Exceedance water level for Ulladulla

5.1.2 Extreme tidal anomaly level

Figure 5.4 shows a summary of extreme value analysis of tidal anomalies for the ocean port and bay sites in NSW. Port Stephens recorded the highest tidal anomalies for both the 20-year (0.55 m) and 100-year (0.67 m) ARI return periods. Jervis Bay recorded the lowest tidal anomalies for both the 20-year (0.43 m) and 100-year (0.47 m) ARI return periods. Increase in anomalies were recorded at the very south of the state (Eden and Bermagui stations), potentially associated with storms near Bass Strait and the Southern Ocean. Additional alongshore variability in extreme ocean water levels may also be attributed to non-astronomical factors associated with extreme tidal anomalies.

Higher tidal anomalies are recorded at seiche-affected sites including Coffs Harbour, Crowdy Head and Ulladulla. Low pass filters have been applied at water level gauges with known seiching. The extreme tidal anomaly analysis for Patonga was omitted due to the existence of some invalid data that created a bias in the results. It is recommended to further analyse the specific events and the measurement methodologies used for stations which are now being recorded at more frequent intervals such as Patonga.

When completing the ocean water level analysis, harmonic analysis remains the best option in the determination of the tidal signal and residuals. Non-astronomical factors (e.g. currents, wind, wave, tsunamis) can have significant impacts on elevated ocean levels and should be considered carefully when interpreting results. Longer-term variability such as the influence of ENSO/SOI and ocean current transports as well as coastally trapped waves have the strongest influence on water levels. Other factors include waves, inverse barometric effect and wave/wind setup.



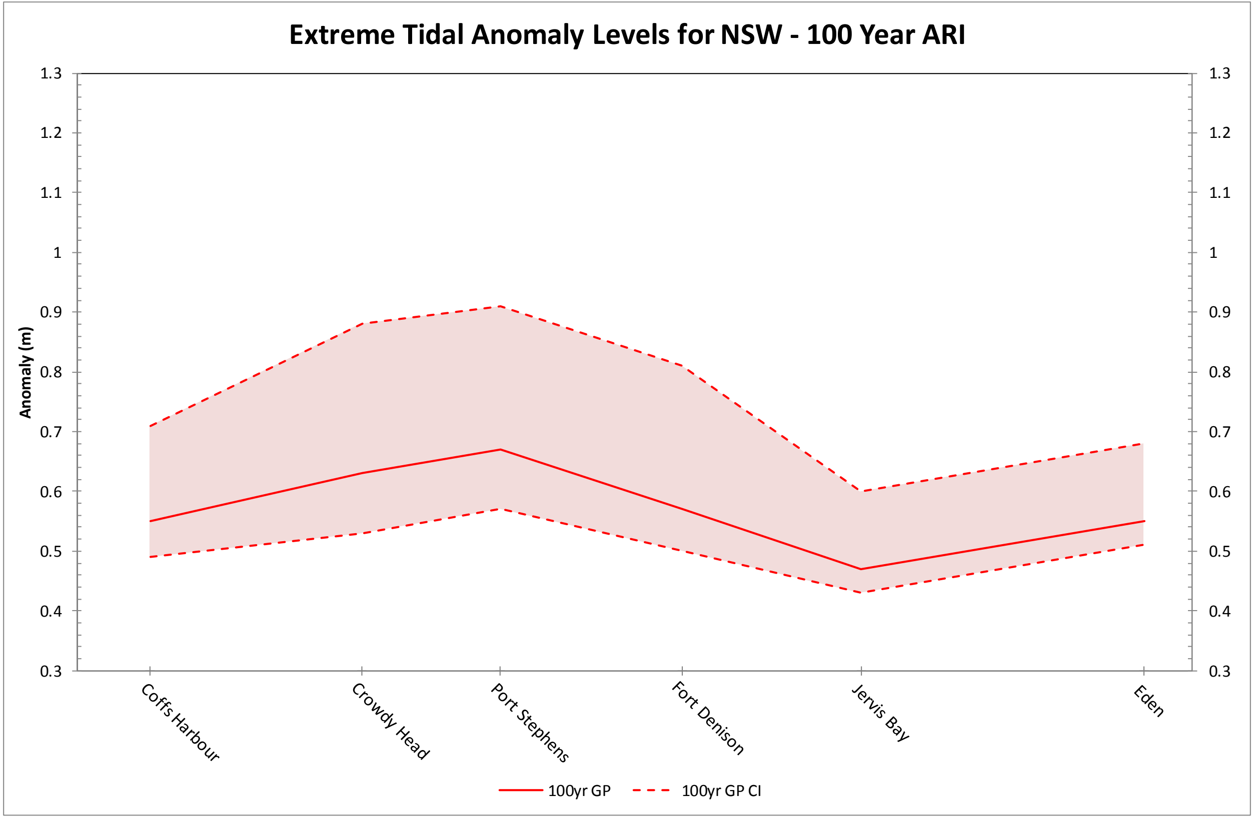


Figure 5.4 Extreme tidal anomaly level plots for NSW coastline with 20-year and 100-year GP model with upper and lower confidence intervals

5.2 Tidal Planes

Figure 5.5 shows the tidal ranges for ocean port and bay gauges in NSW for 20-year ARI and 100-year ARI. The Mean Sea Level (MSL) tidal plane along the NSW coast is relatively consistent, within ±0.05 m AHD, except for at Eden where a MSL of approximately -0.09 m AHD is observed. The High High Water Solstices Springs (HHWSS) tidal plane is also relatively consistent alongshore between 0.95 and 1.05 m AHD, except at the most northern and southern stations of Coffs Harbour and Eden, where this is observed to be slightly higher (1.08 m AHD) and lower (0.89 m AHD) respectively. Alongshore variability in the upper tidal planes (HHWSS and MHWS) may potentially account for some of the observed alongshore trends in extreme ocean water levels.

Alongshore variability is further evident in the mean spring tidal ranges, mean tidal range and mean neap tidal range corresponding to the NSW tidal planes shown in **Figure 5.6**. The findings indicate a uniform decrease in tidal range from north to south along the NSW coast. Mean Spring Tidal Range is approximately 0.23 m larger at Coffs Harbour (1.38 m) than at Eden (1.15 m). This decreasing trend is particularly driven by higher Mean High Water Springs (MHWS) observed in the north of the state compared to the south (**Figure 5.5**) and may also account for some of the alongshore trends in extreme ocean water levels.

Ranking, tidal planes and frequency distribution analysis results for Fort Denison ocean water level gauge data are presented in **Appendix B** as an example of some of the typical analysis that can be undertaken on ocean water levels.

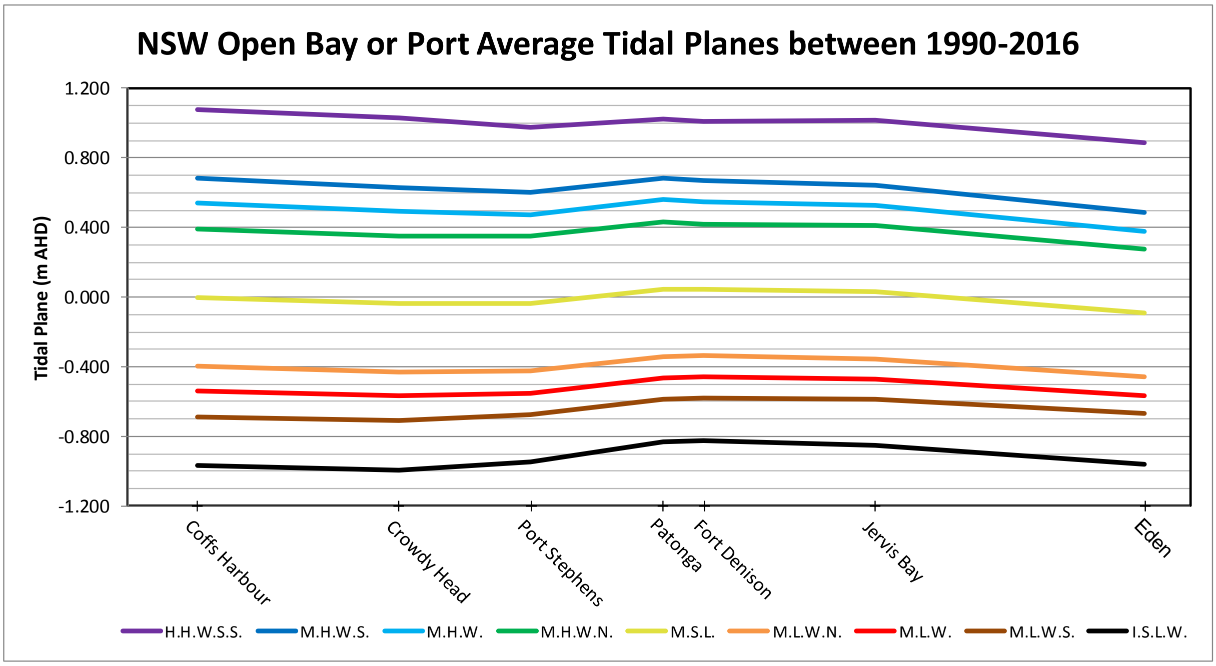


Figure 5.5 NSW open bay or port mean tidal planes between 1990-2016

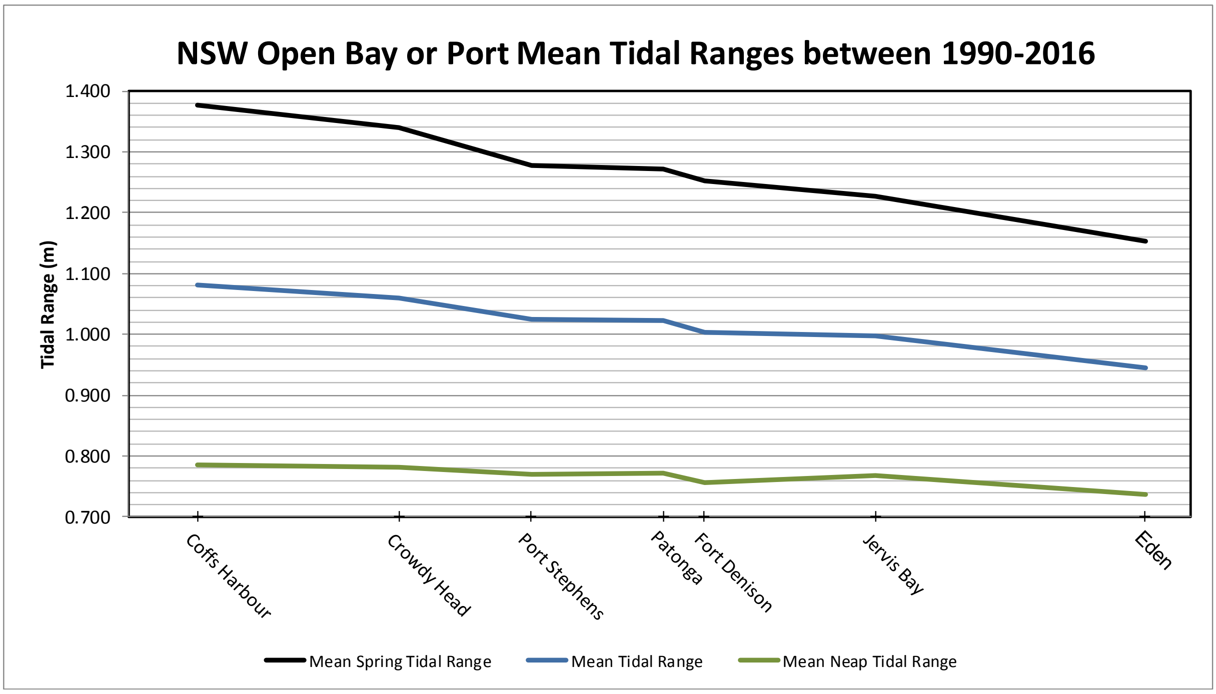


Figure 5.6 NSW open bay or port mean spring tidal range, mean tidal range and mean neap tidal range between 1990-2016

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6. Conclusions and recommendations

A detailed study of the OEH network of gauges in NSW was conducted, providing an accurate and authoritative analysis of extreme water levels for use in planning, engineering and management of the NSW coastline. The study has incorporated the best available knowledge for analysing extreme ocean water levels, tides and tidal anomalies in NSW. Extreme value analysis was undertaken at seven ocean water level stations spread along the NSW coast, from Eden in the south to Coffs Harbour in the north. The findings provide details of the recurrence of extreme ocean water levels as well as extreme tidal anomalies for NSW including probability and cumulative distributions for each station.

6.1 Conclusions

The 20-year and 100-year ARI extreme water levels were calculated along the NSW coastline using a Generalised Pareto model fit with 95% confidence intervals. The 20-year ARI extreme water levels vary from 1.25 m ± 0.1 m in the south of the state at Eden, to 1.43 m ± 0.2 m in the north of the state at Coffs Harbour. Likewise, 100-year ARI extreme water levels also varied along the coast, from 1.30 m ± 0.2 m at Eden to 1.49 m ± 0.4 m at Coffs Harbour. The findings indicate an approximate 0.2 m decreasing trend in extreme ocean water levels from north to south along the NSW coastline with non-uniformities around Port Stephens (negative) and Patonga (positive).

The Fort Denison 100-year ARI is estimated to be 1.42 m. This indicates that the highest recorded water level at Fort Denison of 1.48 m AHD on 25 May 1974, based on more than 100 years of records, could be characterised by an ARI slightly greater than 100 years. It is noted that the ARI for the 1974 event could range from between 50 years to greater than 200 years based on the confidence limits of the extreme value analysis.

Results of tidal planes analysis along NSW show the Mean Sea Level (MSL) to be relatively consistent, within ± 0.05 m AHD, except at Eden where MSL is approximately -0.09 m AHD. Alongshore variability in the upper tidal planes (HHWSS and MHWS) along the NSW coast may potentially account for some of the observed alongshore trends in extreme ocean water levels. It should be noted that the alongshore trends in extreme ocean water levels and tidal planes from north to south along the NSW coastline are not indicative of sea level rise trends.

Additional alongshore variability in extreme ocean water levels may also be attributed to non-astronomical components as shown by extreme tidal anomalies in **Figure ES3**. Port Stephens recorded the highest tidal anomalies for both the 20-year (0.55 m) and 100-year (0.67 m) ARI return periods. Jervis Bay recorded the lowest tidal anomalies for both the 20-year (0.43 m) and 100-year (0.47 m) ARI return periods. Higher anomalies are also recorded at seiche-affected sites including Coffs Harbour, Crowdy Head and Ulladulla. Low pass filters have been applied at water level gauges with known seiching.

6.2 Recommendations

The following recommendations are made to further improve analysis of extreme water levels for use in planning, engineering and management of the NSW coastline:

- Maintain the continual data capture by MHL on all coastal port and bay stations to improve NSW extreme ocean water level analysis. Extreme water level fitting is shown to significantly improve with longer data records and increased sample size. Extreme ocean water level analysis for NSW should be regularly updated as the length of available data records increase.
- Investigate potential sites for placement of onshore open ocean and open bay stations north of Port Macquarie to obtain an improved understanding of the ocean water level along the northern NSW coastline.
- Caution is required when extrapolating estimated extreme ocean water levels beyond the record length (typically 30 years in the present study). It is recommended that sampling, statistical method and climatic variability are considered when selecting appropriate design ocean stillwater levels. Depending on the consequences of exceedance and the ability for cost effective future adaptation, an appropriate contingency may be necessary to account for these uncertainties.
- Continue to examine the various uncertainties associated with extreme value analysis of ocean water levels including the limitations imposed by record length.
- Undertake case study designs using the information provided in this report to develop a methodology for typical case uses.
- Undertake further analysis of the recent high frequency logged data to provide a better understanding of the influence of sampling frequency and reduce the influence of local effects.
- Consider the use of filtering techniques such as low pass filters to pre-process data at all locations to remove signal noise at targeted frequencies associated with non-astronomical forces, wind waves and other short period waves.
- Consider detrending of the data to improve confidence interval and remove non-stationary factors (e.g., climate change). The effects of longer-term sea level rise and other potential effects associated with future climate change should be considered in the estimation of appropriate design water levels in NSW (based on the best available relevant science). Monitoring of mean sea level along the NSW coastline should be undertaken at regular intervals to observe any changes in temporal trends.
- Undertake exceedance-duration analysis to provide additional information on the probability that an extreme ocean water level event will exceed a threshold for a given duration.
- Investigate the effects of negative anomalies (set down) and undertake extreme value analysis of low waters. Most NSW port operations rely on accurate ocean water level predictions to determine under keel clearances and conditions under which the port may become inoperable. Extreme value analysis of low waters could provide valuable economic and environmental input to achieve more effective planning and operation of NSW ports.

7. References

Callaghan, D.P., 2008. Coastal hazards, severe storms in New South Wales. Analysis report, Civil Engineering, The University of Queensland, Brisbane.

Callaghan, D. P., Couriel, E., Hanslow, D., Modra, B., Fitzhenry, M. and Jacobs, R., 2017. Comparing extreme water levels using different techniques and impact of climate indices, *Coasts & Ports 2017 Conference*, June 2017, Cairns, Australia.

Church, J. A. and Freeland, H. J., 1987. The energy source for the coastal-trapped waves in the Australian Coastal Experiment region, *Journal of Physical Oceanography*, 17 (3): 289-300.

Church, J. A., Clarke, A. J., White, N. J., Freeland, H. J. and Smith, R. L., 1990. Energy conservation in the Australian coastal experiment: coastal-trapped wave calculations, *Journal of Physical Oceanography*, 20 (7): 1113-1114.

Church, J. A., White, N. J., Clarke, A. J., Freeland, H. J. and Smith, R. L., 1986a. Coastal-trapped waves on the east Australian continental shelf. Part 2: Model verification. *Journal of Physical Oceanography*, 16 (11): 1945-1957.

Church, J. A., Freeland, H. J. and Smith, R. L., 1986b. Coastal-trapped waves on the east Australian continental shelf. Part 1: Propagation of modes, *Journal of Physical Oceanography*, 16 (11): 1929-1943.

Church, J.A., Hunter, J.R., McInnes, K.L. and White, N.J., 2006. Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events, *Australian Meteorological Magazine*, 55, 253-260.

Coles, S., 2001. Introduction to Statistical Modelling of Extreme Values, Springer Series in Statistics, ISSN 0172-7397, London, UK.

DECCW 2009. NSW Sea Level Rise Policy Statement, Department of Environment, Climate Change and Water, NSW Government. URL: http://www.environment.nsw.gov.au/resources/climatechange/09708sealevrisepolicy.pdf

Ferro, C.A.T. and Segers, J., 2003. Inference for clusters of extreme values. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, Vol. 65 No. 2: 545-556.

Flather, R., Baker, T., Woodworth, P., Vassie, I. and Blackman, D., 2001. Integrated Effects of Climate Change on Coastal Extreme Sea Levels, Proudman Oceanographic Laboratory, Internal Document No. 140.

Folland, C.K., Parker, D.E., Colman, A. and Washington, R., 1999. Large scale modes of ocean surface temperature since the late nineteenth century. Refereed book: Chapter 4, pp73-102 of *Beyond El Nino: Decadal and Interdecadal Climate Variability.* Ed: A. Navarra. Springer-Verlag, Berlin, pp 374.

Folland, C., 2008. Interdecadal Pacific Oscillation Time Series, Met Office Hadley Centre for Climate Change, Exeter, UK.

Foreman, M.G.G. & Neufield, E.T., 1991. Harmonic Tidal Analysis of Long Time Series, International Hydrographic Review, Monaco, LXVIII.

Foreman, M.G.G., 1979. Manual for Tidal Heights Analysis and Prediction, Institute of Ocean Sciences, Patricia Bay, Canada.

Freeland, H. J., Boland, F. M., Church, J. A., Clarke, A. J., Forbes, A. M. G., Huyer, A., Smith, R. L., Thompson, R. O. R. Y. and White, N. J., 1986. The Australian coastal experiment: a search for coastal-trapped waves, *Journal of Physical Oceanography*, 16 (7): 1230-1249.

Godin, G., 1972. The Analysis of Tides, University of Toronto Press.

Holbrook, N.J., Goodwin, I.D., McGregor, S., Molina, E. and Power, S.B., 2011. ENSO to multi-decadal time scale changes in East Australian Current transports and Fort Denison sea level: Oceanic Rossby waves as the connecting mechanism, *Deep Sea Research Part II: Topical Studies in Oceanography*, Vol. 58 No. 5: 547-558.

Lawson, N.V., and Youll, P.H., 1977. Storm Duration and Return Interval for Waves off the Central N.S.W. Coast [online]. In: *Third Australian Conference on Coastal and Ocean Engineering*, 1977: The Coast, the Ocean and Man, Thebarton, ACT.: Institution of Engineers, Australia: 119-126.

Maiwa, K., Masumoto, Y., and Yamagata, T., 2010. Characteristics of coastal trapped waves along the southern and eastern coasts of Australia , *J. Oceanogr*., 66, 243–258.

Manly Hydraulics Laboratory, 1992. Mid New South Wales Coastal Region Tide-Storm Surge Analysis, MHL Report 621, October 1992.

Manly Hydraulics Laboratory, 1995. The Harmonic Analysis of NSW Tide Gauge Network Volume 1 Tidal Planes, MHL Report 604.

Manly Hydraulics Laboratory, 1995. The Harmonic Analysis of NSW Tide Gauge Network Volume 2 Tidal Phases, MHL Report 604.

Manly Hydraulics Laboratory, 2003. DLWC NSW Tidal Planes Data Compilation 2001 Volume 1 Tidal Planes Analysis, MHL Report 1098, March 2003.

Manly Hydraulics Laboratory, 2005. Investigation into Tidal Planes Compilation, DNR NSW Tidal Planes Data Compilation Stage 3, MHL Report 1269, November 2005.

Manly Hydraulics Laboratory, 2011. NSW Ocean Water Levels, MHL Report 1881, March 2011.

Manly Hydraulics Laboratory, 2012. OEH NSW Tidal Planes Analysis, MHL Report 2053, October 2012.

Manly Hydraulics Laboratory, 2013. National and NSW Tide Gauge Histories, MHL Report 2179, October 2013.

Manly Hydraulics Laboratory, 2013. North Coast Ocean Tide Site Scoping Study, MHL Report 2072, September 2013.

Manly Hydraulics Laboratory, 2014. OEH NSW Water Level Frequency Distribution Analysis, MHL Report 2100, March 2014.

Manly Hydraulics Laboratory, 2014. MHL Tidal Methodology Review, MHL Report 2156 (in draft).

Manly Hydraulics Laboratory, 2015. NSW Ocean and River Entrance Tidal Levels Annual Summary 2014–2015, MHL 2384, November 2015.

Manly Hydraulics Laboratory, 2016. NSW Ocean and River Entrance Tidal Levels Annual Summary 2015-2016, MHL 2475, October 2016.

McInnes, K. L., Abbs, D. J., and Bathols, J. M., 2005. Climate change in Eastern Victoria. Stage 1 report: the effect of climate change on coastal wind and weather patterns: a project undertaken for the Gippsland Coastal Board, CSIRO Marine and Atmospheric Research. Aspendale, Australia.

McInnes, K. L., Macadam, I., Hubbert, G. D., Abbs, D. J., and Bathols, J. M., 2005. Climate change in Eastern Victoria. Stage 2 report: the effect of climate change on storm surges: a project undertaken for the Gippsland Coastal Board, CSIRO Marine and Atmospheric Research. Aspendale, Australia.

McInnes, K.L. and Hubbert G.D., 2001. The impact of eastern Australian cut-off lows on coastal sea levels, *Meteorological Applications*, 8, 229-244.

McIntosh, P. C. and Schahinger, R. B., 1994. Coastal-trapped wave mode fitting: reanalysis of the Australian Coastal Experiment, *Journal of Physical Oceanography*, 24(5): 949-965 32 refs, illus.

Middleton, J. F., 2006. The coastal trapped wave paddle as an open boundary condition, *Ocean Modelling*, 12, 224-236.

Middleton, J. F. and Leth O., 2004. Wind-forced set-up of upwelling, geographical origins and numerical models: the role of bottom drag, *J. Geophys. Res*., 109, C12019.

Nielsen, P., 2009. Coastal and estuarine processes, Advanced series on ocean engineering, *World Scientific*, Singapore, 341 pp.

NSW Government, 1990. Coastline Management Manual*,* ISBN 0 73057 506 3, September.

Peltier, W.R., 1998. Postglacial Variations in the Level of the Sea: Implications for Climate Dynamics and Solid-Earth Geophysics, *Reviews of Geophysics* 1998. 36(4),603-689.

Peltier, W.R., 2004. Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G(VM2) model and GRACE, *Ann. Rev. Earth. Planet. Sci*. 2004. 32,111-149.

Peltier, W.R., 2005. On the Hemispheric Origins of Meltwater Pulse 1A. *Quat. Sci. Rev*., 24, 1655-1671.

Pilgrim, D.H. and Doran, D.G., 1999. Selection and Evaluation of Parent Distributions, Flood Frequency Analysis, CRC Press, eds. A. Ramachandra Rao and Khaled H. Hamed, October 1999.

Pugh, D.T. and Vassie, J.M., 1979. Extreme sea levels from tide and surge probability, pp.911-930 in vol 1, *Proceedings of the sixteenth Coastal Engineering Conference*, 1978, Hamburg, Germany. New York: American society of Civil Engineers. 3060pp.

R Development Core Team, 2008. R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org

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Sobey, R.J. and Orloff, L.S., 1998. Duration in wave climate analysis, In Coastal engineering ’98, *Proceedings of the American Society of Civil Engineers Conference*, Copenhagen, Denmark. pp. 1013–1026.

Sobey, R.J. and L.S. Orloff. 1999. Intensity-duration-frequency summaries for wave climate, *Coastal Eng*. 36:37-58.

White, N. J., Haigh, I. D., Church, J. A., Koen, T., Watson, C. S., Pritchard, T. R., Watson, P. J., Burgette, R. J., McInnes, K. L. and You, Z. J. 2014. Australian sea levels—Trends, regional variability and influencing factors, *Earth-Science Reviews*, 136, 155-174.

Woodham, R., Brassington, G.B., Robertson, R. and Alves, O., 2013. Propagation Characteristics of Coastally Trapped Waves on the Australian Continental Shelf, *Journal of Geophysical Research: Oceans*. 118:4461–4473.

Appendix A. Harmonic constituents

Table A1 Characteristics of harmonic constituents generated by Foreman analysis programme

Constituent no.	Name	Description	Frequency (cycles/hr)	Period (days, hrs)
1	Z0	Mean sea level		
2	SA	Solar annual	0.0001141	365d,06h
3	SSA	Solar semi-annual	0.0002282	182d,15h
4	MSM		0.0013098	31d,19h
5	MM	Lunar monthly	0.0015122	27d,13h
6	MSF	Lunisolar synodic fortnightly	0.0028219	14d,18h
7	MF	Lunar fortnightly	0.0030501	13d,16h
8	ALP1		0.0343966	29.07h
9	2Q1	Lunar elliptic diurnal	0.0357063	28.01h
10	SIG1		0.0359087	27.85h
11	Q1	Larger lunar elliptic diurnal	0.0372185	26.87h
12	RHO1		0.0374209	26.72h
13	O1	Lunisolar diurnal	0.0387307	25.82h
14	TAU1		0.0389588	25.67h
15	BET1		0.0400404	24.97h
16	NO1		0.0402686	24.83h
17	CHI1		0.040471	24.71h
18	PI1		0.0414385	24.13h
19	P1	Solar diurnal	0.0415526	24.07h
20	S1	Solar diurnal	0.0416667	24.00h
21	K1	Luni-solar diurnal	0.0417807	23.93h
22	PSI1		0.0418948	23.87h
23	PHI1		0.0420089	23.80h
24	THE1		0.0430905	23.21h
25	J1	Smaller lunar elliptic diurnal	0.0432929	23.10h
26	SO1	Shallow water (S2&O1)	0.0446027	22.42h
27	OO1	Lunar diurnal 2nd order	0.0448308	22.31h
28	UPS1		0.046343	21.58h
29	OQ2		0.0759749	13.16h
30	EPS2		0.0761773	13.13h
31	2N2	Lunar elliptic semi-diurnal 2nd order	0.0774871	12.91h
32	MU2	Variational	0.0776895	12.87h
33	N2	Larger luni-elliptic semi-diurnal	0.0789993	12.66h
34	NU2	Larger lunar evectional	0.0792016	12.63h

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Constituent no.	Name	Description	Frequency (cycles/hr)	Period (days, hrs)
35	H1		0.0803973	12.44h
36	M2	Principal lunar semi-diurnal	0.0805114	12.42h
37	H2		0.0806255	12.40h
38	MKS2	Shallow water (M2&K2&S2)	0.0807396	12.39h
39	LDA2		0.0818212	12.22h
40	L2	Smaller lunar elliptic semi-diurnal	0.0820236	12.19h
41	T2	Larger solar elliptic	0.0832193	12.02h
42	S2	Principal solar semi-diurnal	0.0833333	12.00h
43	R2	Smaller solar elliptic semi-diurnal	0.0834474	11.98h
44	K2	Luni-solar semi-diurnal	0.0835615	11.97h
45	MSN2	Shallow water (M2&S2&N2)	0.0848455	11.79h
46	ETA2		0.0850736	11.75h
47	MO3	Shallow water (M2&O1)	0.1192421	8.39h
48	M3	Lunar terdiurnal	0.1207671	8.28h
49	SO3	Shallow water (S2&O1)	0.122064	8.19h
50	MK3	Shallow water (M2&K1)	0.1222921	8.18h
51	SK3	Shallow water (S2&K1)	0.1251141	7.99h
52	MN4	Shallow water (M2&N2)	0.1595106	6.27h
53	M4	Shallow water (M2)	0.1610228	6.21h
54	SN4	Shallow water (S2&N2)	0.1623326	6.16h
55	MS4	Shallow water (M2&S2)	0.1638447	6.10h
56	MK4	Shallow water (M2&K2)	0.1640729	6.09h
57	S4	Shallow water (S2)	0.1666667	6.00h
58	SK4	Shallow water (S2&K2)	0.1668948	5.99h
59	2MK5	Shallow water (M2&K1)	0.2028036	4.93h
60	2SK5	Shallow water (S2&K1)	0.2084474	4.80h
61	2MN6	Shallow water (M2&N2)	0.240022	4.17h
62	M6	Shallow water (M2)	0.2415342	4.14h
63	2MS6	Shallow water (M2&S2)	0.2443561	4.09h
64	2MK6	Shallow water (M2&K2)	0.2445843	4.09h
65	2SM6	Shallow water (S2&M2)	0.2471781	4.05h
66	MSK6	Shallow water (M2&S2&K2)	0.2474062	4.04h
67	3MK7	Shallow water (M2&K2)	0.2833149	3.53h
68	M8	Shallow water (M2)	0.3220456	3.11h
69	M10	Shallow water (M2)	0.402557	2.48h

Appendix B. Example water level analysis Fort Denison

The results of ranking, tidal planes and frequency distribution analysis are presented in this appendix for Fort Denison ocean water level gauge data. A summary of the analysis is provided below.

Table 1: Ranking of Highest Recorded Water Levels

The highest recorded water levels are ranked according to the peak level achieved in the event, and are listed in this table with relevant information about the event: peak level, date, and duration. Both original (**Table B1.1**) and detrended (**Table B1.2**) are presented.

Note that there is a tendency for peak levels to occur on consecutive days at similar times. This is a normal result of astronomical tides driving peak water levels on a daily cycle, with the highest events occurring when a positive anomaly occurs near highest astronomical tide. No attempt has been made to decluster these events, with preference to presenting data as it appears.

Table 2: Ranking of Highest Recorded Anomalies

The highest recorded anomalies are ranked according to the peak level achieved in the event, and are listed in this table with relevant information about the event: peak level, date, and duration. Both original (**Table B1.3**) and detrended (**Table B1.4**) are presented.

Anomaly events were identified by the exceedance of the residual over a threshold level, which is chosen to be 0.2 m for this study. This value was selected to ensure that there is an appropriate number of anomaly events selected that are neither too small nor too large.

Ideally, events should be separated by inspection of the processes driving the anomaly, but this is time consuming and outside the scope of this project. Choosing a maximum period for which an even can drop below the threshold allows the automated identification of anomalies – a period of 1 hour has been employed for this report.

Table 3: Tidal Planes

Tidal planes derived from the major constituents of a harmonic analysis performed on yearly data are presented in **Table B2**. Tidal planes for all stations in the OEH network are presented in MHL2053 *OEH NSW Tidal Planes Analysis 1990–2010 Harmonic Analysis*, along with the derivation on the planes and associated methodology. **Figure 5.1** shows the mean sea level range deviations along the NSW coastline which are determined using the tidal planes method.

Figure 1: Frequency Distribution of Recorded Water Levels

Following the method and presentation of results in MHL2100 *OEH NSW Water Level Frequency Distribution Analysis* (2014), the probability distribution and cumulative distribution of water levels for Fort Denison are provided. **Figure B1.1** shows the distribution of measured water levels at the station without detrending and **Figure B1.2** shows the log representation of this distribution. **Figure B1.3** shows the distribution of measured water levels at the station with detrending and **Figure B1.4** shows the log representation of this distribution.

These figures are appropriate for investigations of tide levels near the dominant mode, over the majority of the tide range. However, for extreme events forecast levels based on the extreme value analysis are more appropriate, and are provided in **Figure 5.2** and **Figure 5.3**.

Figure 2: Frequency Distribution of Tidal Residuals

Frequency distribution analysis for the tidal residuals was also conducted and presented. **Figure B2.1** shows the distribution of tidal residuals at the station without detrending and **Figure B2.2** shows the log representation of this distribution. **Figure B2.3** shows the distribution of tidal residual with detrending and **Figure B2.4** shows the log representation of this distribution.

Table B1 Fort Denison water level analysis

General information	
Site Name	Fort Denison
Location	Sydney Harbour
Period of Data	1914-Present
Period of Analysis	01/06/1914-01/01/2017
AWRC	60370
MGA Zone	56
Easting	335865.89
Northing	6252542.11
Datum	Zero Fort Denison Tide Gauge
Adjustment to AHD (m)	-0.925
Classification	Onshore Bay or Port
Logger	not available
Primary Sensor	Searanger sonic sensor
Secondary Sensor	none

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Table B1.1 Ranking of highest recorded water levels without detrending

Classification	Onshore Bay or Port
Datum	Australian Height Datum
Period of Analysis	01/06/1914-01/01/2017

Rank	Date/Time	WSL AHD (m)	Duration
1	25/05/1974 23:00	1.480	6
2	27/04/1990 22:00	1.430	5
3	10/06/1956 21:00	1.400	4
4	01/07/1984 22:00	1.350	5
5	19/08/2001 20:00	1.340	4
6	10/07/1964 21:00	1.340	5
7	15/06/2014 22:00	1.330	5
8	22/07/1978 22:00	1.310	5
9	03/08/1921 20:00	1.300	5
10	12/12/1950 10:00	1.290	4
11	04/07/2016 20:00	1.290	5
12	14/06/1999 21:00	1.290	4
13	14/06/2007 20:00	1.290	4
14	19/06/1947 21:00	1.280	4
15	04/06/2012 20:00	1.280	5
16	02/06/1973 21:00	1.270	5
17	09/06/1974 23:00	1.270	3
18	20/07/1974 20:00	1.270	5
19	02/06/1977 21:00	1.270	4
20	29/06/1977 19:00	1.270	4
21	04/06/1985 21:00	1.270	5
22	12/07/1991 21:00	1.270	4
23	30/07/1992 21:00	1.270	4
24	02/01/2014 09:00	1.270	4
25	23/06/1998 20:00	1.270	4
26	05/06/2016 20:00	1.270	4
27	24/05/1959 22:00	1.260	4
28	12/05/1960 21:00	1.260	4
29	11/06/1964 21:00	1.260	4
30	14/05/1968 22:00	1.260	4
31	01/06/1969 21:00	1.260	4
32	24/06/2013 21:00	1.260	5
33	15/06/2003 21:00	1.260	5
34	14/02/1949 09:00	1.250	4
35	30/12/1959 08:00	1.250	4
36	18/02/1984 09:00	1.250	4
37	22/06/1986 20:00	1.250	4
38	13/07/1995 21:00	1.250	4
39	01/01/2002 09:00	1.250	4
40	22/07/2009 21:00	1.250	4

Data courtesy of Sydney Port Corporation and BoM. Data time stamp in GMT

Table B1.2 Ranking of highest recorded water levels with detrending

Rank	Date/Time	WSL AHD (m)	Duration
1	25/05/1974 23:00	1.520	6
2	10/06/1956 21:00	1.460	5
3	27/04/1990 22:00	1.450	5
4	03/08/1921 20:00	1.400	5
5	10/07/1964 21:00	1.390	5
6	01/07/1984 22:00	1.380	5
7	12/12/1950 10:00	1.360	4
8	19/08/2001 20:00	1.360	4
9	19/06/1947 21:00	1.360	4
10	22/07/1978 22:00	1.350	5
11	27/06/1915 20:00	1.350	4
12	15/06/2014 22:00	1.340	5
13	18/06/1935 21:00	1.330	4
14	14/02/1949 09:00	1.330	4
15	24/05/1959 22:00	1.320	4
16	12/05/1960 21:00	1.320	4
17	02/06/1973 21:00	1.320	5
18	11/06/1964 21:00	1.320	4
19	09/06/1974 23:00	1.320	3
20	20/07/1974 20:00	1.320	5
21	02/06/1977 21:00	1.320	4
22	29/06/1977 19:00	1.320	4
23	14/05/1968 22:00	1.320	4
24	01/06/1969 21:00	1.310	4
25	30/12/1959 08:00	1.310	4
26	24/02/1925 09:00	1.310	4
27	14/06/1999 21:00	1.310	4
28	04/06/1985 21:00	1.310	5
29	05/05/1958 22:00	1.310	4
30	17/12/1929 08:00	1.310	4
31	18/06/1932 20:00	1.300	5
32	12/07/1991 21:00	1.300	4
33	30/07/1992 21:00	1.300	4
34	22/04/1936 21:00	1.300	4
35	14/06/2007 20:00	1.300	4
36	14/04/1937 23:00	1.300	5
37	31/05/1938 22:00	1.300	4
38	10/12/1938 10:00	1.300	5
39	04/07/2016 20:00	1.300	5
40	25/01/1940 08:00	1.300	4

Table B1.3 Ranking of highest recorded anomalies without detrending

Rank	Date/Time	Anomaly (m)	Duration (H)
1	26/05/1974 02:00	0.570	96
2	06/07/1931 23:00	0.550	101
3	02/06/1978 04:00	0.530	5
4	10/06/1974 18:00	0.510	92
5	13/06/1966 12:00	0.460	69
6	19/04/1927 01:00	0.460	56
7	29/01/1978 11:00	0.430	48
8	18/02/1962 07:00	0.400	28
9	05/04/1951 16:00	0.400	199
10	15/06/1978 11:00	0.400	45
11	04/08/1921 00:00	0.400	186
12	02/07/1921 02:00	0.390	4
13	08/04/1921 22:00	0.390	122
14	07/08/1998 20:00	0.390	65
15	27/04/1990 18:00	0.380	162
16	21/06/1975 06:00	0.380	28
17	11/05/1997 04:00	0.380	62
18	22/02/1954 09:00	0.380	87
19	23/06/1965 07:00	0.380	65
20	05/07/1984 00:00	0.370	81
21	19/01/1950 04:00	0.370	24
22	15/03/1938 04:00	0.370	105
23	08/04/1945 06:00	0.370	54
24	01/05/1966 08:00	0.370	99
25	04/02/1990 23:00	0.370	67
26	21/05/1966 11:00	0.360	31
27	15/04/1948 21:00	0.360	98
28	19/08/1973 23:00	0.360	1
29	28/02/1940 01:00	0.360	88
30	03/08/1990 11:00	0.350	2
31	14/07/1964 07:00	0.350	173
32	07/08/1986 00:00	0.350	72
33	11/03/1958 02:00	0.350	119
34	03/01/1922 00:00	0.350	46
35	07/07/1932 20:00	0.350	75
36	07/10/1928 13:00	0.350	82
37	30/08/1963 06:00	0.350	61
38	29/07/2001 04:00	0.340	63
39	10/06/1915 14:00	0.340	61
40	19/05/1915 14:00	0.340	83

Table B1.4 Ranking of highest recorded anomalies with detrending

Rank	Date/Time	Anomaly (m)	Duration (H)
1	26/05/1974 02:00	0.570	96
2	06/07/1931 23:00	0.550	101
3	02/06/1978 04:00	0.530	5
4	10/06/1974 18:00	0.510	92
5	13/06/1966 12:00	0.460	69
6	19/04/1927 01:00	0.460	56
7	29/01/1978 11:00	0.430	48
8	18/02/1962 07:00	0.400	28
9	05/04/1951 16:00	0.400	199
10	15/06/1978 11:00	0.400	45
11	04/08/1921 00:00	0.400	186
12	02/07/1921 02:00	0.390	4
13	08/04/1921 22:00	0.390	122
14	07/08/1998 20:00	0.390	65
15	27/04/1990 18:00	0.380	162
16	21/06/1975 06:00	0.380	28
17	11/05/1997 04:00	0.380	62
18	22/02/1954 09:00	0.380	87
19	23/06/1965 07:00	0.380	65
20	05/07/1984 00:00	0.370	81
21	19/01/1950 04:00	0.370	24
22	08/04/1945 06:00	0.370	54
23	15/03/1938 04:00	0.370	105
24	01/05/1966 08:00	0.370	99
25	04/02/1990 23:00	0.370	67
26	21/05/1966 11:00	0.360	31
27	15/04/1948 21:00	0.360	98
28	19/08/1973 23:00	0.360	1
29	28/02/1940 01:00	0.360	88
30	03/08/1990 11:00	0.360	2
31	14/07/1964 07:00	0.350	173
32	07/08/1986 00:00	0.350	72
33	03/01/1922 00:00	0.350	46
34	11/03/1958 02:00	0.350	119
35	07/07/1932 20:00	0.350	75
36	07/10/1928 13:00	0.350	82
37	30/08/1963 06:00	0.350	61
38	29/07/2001 04:00	0.340	63
39	10/06/1915 14:00	0.340	61
40	19/05/1915 14:00	0.340	83

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Table B2 Tidal planes analysis – Fort Denison

Classification	Onshore Bay or Port
Datum	Zero Fort Denison
Period of Analysis	01/06/1914-30/06/2016

Start Date	01/06/14	30/06/14	30/06/15	30/06/16	30/06/17	30/06/18	30/06/19	30/06/20	30/06/21	30/06/22	30/06/23	30/06/24	30/06/25	30/06/26	30/06/27	30/06/28	30/06/29	01/01/31	30/06/31	30/06/32
End Date	02/06/15	01/07/15	30/06/16	01/07/17	01/07/18	01/07/19	30/06/20	01/07/21	01/07/22	01/07/23	30/06/24	01/07/25	01/07/26	01/07/27	30/06/28	01/07/29	01/01/31	02/01/32	30/06/32	01/07/33
TIDAL PLANES (m)																				
H.H.W.S.S.	1.926	1.930	1.888	1.920	1.893	1.888	1.877	1.893	1.964	1.876	1.874	1.871	1.871	1.879	1.838	1.900	1.806	1.905	1.895	1.894
M.H.W.S.	1.585	1.588	1.538	1.574	1.550	1.548	1.536	1.554	1.614	1.531	1.533	1.523	1.523	1.533	1.494	1.554	1.419	1.556	1.548	1.549
M.H.W.	1.456	1.458	1.410	1.445	1.425	1.423	1.410	1.428	1.487	1.405	1.405	1.394	1.395	1.405	1.366	1.425	1.287	1.425	1.418	1.419
M.H.W.N.	1.327	1.329	1.283	1.316	1.299	1.298	1.284	1.303	1.360	1.279	1.278	1.265	1.268	1.277	1.237	1.295	1.155	1.293	1.287	1.290
M.S.L.	0.938	0.941	0.897	0.925	0.908	0.904	0.894	0.911	0.962	0.883	0.880	0.867	0.867	0.882	0.840	0.897	0.767	0.899	0.891	0.895
M.L.W.N.	0.549	0.554	0.511	0.535	0.517	0.511	0.503	0.518	0.564	0.487	0.483	0.469	0.465	0.486	0.442	0.499	0.379	0.504	0.495	0.499
M.L.W.	0.420	0.424	0.384	0.405	0.392	0.386	0.377	0.393	0.437	0.361	0.355	0.340	0.338	0.358	0.314	0.370	0.248	0.372	0.364	0.370
M.L.W.S.	0.291	0.295	0.256	0.276	0.266	0.260	0.252	0.267	0.310	0.235	0.227	0.211	0.210	0.230	0.185	0.240	0.116	0.241	0.234	0.240
I.S.L.W.	0.047	0.051	0.006	0.029	0.021	0.017	0.007	0.025	0.059	-0.011	-0.016	-0.038	-0.038	-0.017	-0.061	-0.007	-0.161	-0.008	-0.014	-0.006
TIDAL RANGES (m)																				
M.N.R. (MHWN-MLWN)	0.778	0.775	0.772	0.781	0.782	0.787	0.781	0.785	0.796	0.792	0.795	0.797	0.802	0.792	0.795	0.796	0.776	0.790	0.793	0.791
M.R. (MHW-MLW)	1.036	1.034	1.027	1.039	1.033	1.037	1.032	1.036	1.050	1.044	1.050	1.054	1.058	1.047	1.052	1.055	1.039	1.052	1.054	1.050
M.S.R. (MHWS-MLWS)	1.294	1.293	1.281	1.298	1.284	1.288	1.284	1.286	1.304	1.297	1.306	1.312	1.313	1.302	1.310	1.314	1.302	1.314	1.315	1.308
R. (HHWSS-ISLW)	1.878	1.878	1.882	1.891	1.872	1.871	1.870	1.868	1.904	1.888	1.889	1.908	1.909	1.896	1.899	1.908	1.967	1.914	1.908	1.900
TIDAL CONSTITUENTS (m)																				
M2	0.518	0.517	0.513	0.520	0.517	0.519	0.516	0.518	0.525	0.522	0.525	0.527	0.529	0.524	0.526	0.527	0.520	0.526	0.527	0.525
S2	0.129	0.129	0.127	0.129	0.125	0.125	0.126	0.125	0.127	0.126	0.128	0.129	0.128	0.128	0.129	0.130	0.132	0.131	0.130	0.129
K1	0.147	0.148	0.152	0.152	0.150	0.147	0.148	0.148	0.152	0.150	0.147	0.151	0.152	0.151	0.150	0.150	0.178	0.151	0.150	0.149
O1	0.096	0.096	0.098	0.095	0.096	0.096	0.096	0.094	0.098	0.097	0.096	0.098	0.097	0.096	0.096	0.098	0.099	0.099	0.097	0.098
MSF	0.018	0.007	0.012	0.013	0.004	0.007	0.011	0.017	0.013	0.015	0.010	0.006	0.009	0.010	0.022	0.020	0.027	0.007	0.004	0.024
TIDAL CONSTITUENTS (deg)																				
M2	239.66	239.79	241.39	240.33	240.81	240.93	240.29	240.42	237.41	239.36	237.91	238.39	237.76	239.41	238.73	237.82	236.31	237.27	237.26	238.06
S2	266.35	266.16	266.88	265.68	265.33	265.82	265.25	265.68	262.55	263.42	263.68	263.72	263.29	263.77	263.02	262.49	263.06	262.51	262.53	263.06
K1	119.85	119.45	121.88	120.95	120.12	120.98	119.44	120.35	119.38	121.16	120.81	119.95	120.21	120.94	118.97	119.17	120.01	120.00	119.29	120.67
O1	80.94	81.08	81.01	80.78	81.79	82.31	79.82	80.94	78.15	79.75	78.34	79.84	80.15	81.63	80.56	79.90	79.28	79.52	80.01	80.40
MSF	184.20	210.39	149.53	51.62	316.09	10.36	102.86	333.50	359.80	140.97	133.32	85.83	103.31	132.41	242.77	138.29	112.64	117.20	167.88	216.82
RMS RESIDUAL ERROR (m)																				
	0.087	0.089	0.077	0.078	0.083	0.080	0.074	0.083	0.091	0.081	0.083	0.080	0.090	0.084	0.076	0.093	0.060	0.074	0.079	0.066
DATA CAPTURE (%)																				
	97.6%	98.8%	98.4%	90.8%	99.6%	97.2%	98.8%	100.0%	99.6%	88.4%	99.2%	100.0%	100.0%	98.0%	100.0%	99.6%	33.6%	100.0%	100.0%	100.0%
COMMENTS																				

Table B2 Tidal planes analysis – Fort Denison (continued)

Classification	Onshore Bay or Port
Datum	Zero Fort Denison
Period of Analysis	01/06/1914-30/06/2016

Start Date	30/06/33	30/06/34	30/06/35	30/06/36	30/06/37	30/06/38	30/06/39	30/06/40	30/06/41	30/06/42	30/06/43	30/06/44	30/06/45	30/06/46	30/06/47	30/06/48	30/06/49	30/06/50	30/06/51	30/06/52
End Date	01/07/34	01/07/35	30/06/36	01/07/37	01/07/38	01/07/39	30/06/40	01/07/41	01/07/42	01/07/43	30/06/44	01/07/45	01/07/46	01/07/47	30/06/48	01/07/49	01/07/50	01/07/51	30/06/52	01/07/53
TIDAL PLANES (m)																				
H.H.W.S.S.	1.877	1.924	1.891	1.899	1.893	1.891	1.899	1.824	1.861	1.889	1.863	1.874	1.899	1.870	1.887	1.890	1.914	1.942	1.948	1.915
M.H.W.S.	1.535	1.579	1.548	1.555	1.551	1.549	1.556	1.483	1.517	1.549	1.521	1.530	1.551	1.525	1.537	1.546	1.567	1.599	1.602	1.571
M.H.W.	1.405	1.449	1.418	1.425	1.422	1.420	1.427	1.357	1.389	1.420	1.392	1.400	1.422	1.396	1.408	1.417	1.437	1.471	1.472	1.444
M.H.W.N.	1.275	1.319	1.288	1.296	1.293	1.292	1.299	1.231	1.261	1.291	1.264	1.271	1.294	1.267	1.279	1.288	1.306	1.342	1.342	1.317
M.S.L.	0.884	0.928	0.893	0.903	0.896	0.900	0.905	0.839	0.870	0.903	0.872	0.873	0.895	0.872	0.884	0.897	0.918	0.950	0.952	0.925
M.L.W.N.	0.493	0.537	0.497	0.509	0.499	0.507	0.511	0.446	0.480	0.514	0.480	0.475	0.495	0.476	0.488	0.507	0.530	0.557	0.562	0.533
M.L.W.	0.363	0.407	0.367	0.380	0.370	0.379	0.383	0.320	0.352	0.385	0.352	0.346	0.367	0.347	0.359	0.378	0.400	0.429	0.431	0.406
M.L.W.S.	0.233	0.277	0.238	0.251	0.242	0.250	0.254	0.194	0.224	0.256	0.224	0.216	0.239	0.218	0.230	0.249	0.269	0.300	0.301	0.279
I.S.L.W.	-0.011	0.031	-0.007	0.005	-0.003	0.006	0.009	-0.049	-0.022	0.013	-0.021	-0.029	-0.010	-0.028	-0.019	0.003	0.022	0.055	0.054	0.033
TIDAL RANGES (m)																				
M.N.R. (MHWN-MLWN)	0.782	0.782	0.791	0.787	0.793	0.784	0.788	0.785	0.782	0.778	0.784	0.796	0.799	0.791	0.791	0.781	0.776	0.785	0.780	0.784
M.R. (MHW-MLW)	1.042	1.042	1.051	1.046	1.051	1.042	1.045	1.037	1.037	1.035	1.040	1.055	1.055	1.048	1.049	1.039	1.037	1.042	1.041	1.038
M.S.R. (MHWS-MLWS)	1.302	1.302	1.310	1.304	1.309	1.299	1.301	1.289	1.293	1.292	1.297	1.313	1.312	1.306	1.307	1.296	1.298	1.299	1.301	1.291
R. (HHWSS-ISLW)	1.889	1.892	1.898	1.894	1.896	1.886	1.890	1.874	1.883	1.876	1.884	1.903	1.908	1.898	1.906	1.886	1.892	1.887	1.894	1.882
TIDAL CONSTITUENTS (m)																				
M2	0.521	0.521	0.525	0.523	0.526	0.521	0.522	0.518	0.519	0.518	0.520	0.527	0.528	0.524	0.524	0.519	0.518	0.521	0.520	0.519
S2	0.130	0.130	0.130	0.129	0.129	0.129	0.128	0.126	0.128	0.129	0.128	0.129	0.128	0.129	0.129	0.129	0.131	0.129	0.130	0.127
K1	0.149	0.148	0.149	0.150	0.148	0.148	0.149	0.147	0.149	0.146	0.149	0.148	0.151	0.150	0.151	0.148	0.150	0.150	0.150	0.150
O1	0.095	0.098	0.097	0.096	0.096	0.096	0.097	0.097	0.097	0.098	0.095	0.097	0.098	0.096	0.099	0.098	0.097	0.096	0.098	0.097
MSF	0.025	0.015	0.007	0.022	0.012	0.010	0.006	0.011	0.022	0.015	0.004	0.003	0.005	0.018	0.022	0.023	0.006	0.006	0.016	0.014
TIDAL CONSTITUENTS (deg)																				
M2	238.09	237.64	237.80	237.60	237.22	237.31	236.42	238.01	238.00	237.84	238.49	238.29	237.69	237.35	236.43	235.71	237.08	237.49	238.04	239.59
S2	263.87	261.91	263.24	262.88	262.11	262.47	261.79	262.14	262.11	261.06	262.17	262.62	261.41	262.04	261.78	261.39	262.97	263.44	263.89	264.68
K1	119.91	119.78	119.83	119.44	118.60	119.91	119.92	118.63	119.63	119.05	118.24	121.03	119.87	119.52	118.97	119.83	119.36	119.92	120.21	120.48
O1	80.08	81.36	80.71	80.16	79.28	78.52	79.05	81.44	80.19	81.03	80.59	79.31	80.25	79.79	79.78	79.80	79.62	80.15	80.35	81.24
MSF	164.33	294.70	100.63	269.50	1.14	111.59	227.30	284.09	33.33	48.68	327.07	230.63	276.95	117.67	223.15	240.56	257.25	250.31	128.92	202.71
RMS RESIDUAL ERROR (m)																				
	0.067	0.073	0.072	0.079	0.077	0.075	0.085	0.079	0.081	0.079	0.083	0.073	0.069	0.060	0.074	0.082	0.076	0.087	0.079	0.074
DATA CAPTURE (%)																				
	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	79.6%	98.0%	96.8%	96.8%	99.6%	100.0%	100.0%	100.0%	99.6%	99.2%	99.6%	100.0%	97.6%

Table B2 Tidal planes analysis – Fort Denison (continued)

Classification	Onshore Bay or Port
Datum	Zero Fort Denison
Period of Analysis	01/06/1914-30/06/2016

Start Date	30/06/53	30/06/54	30/06/55	30/06/56	30/06/57	30/06/58	30/06/59	30/06/60	30/06/61	30/06/62	30/06/63	30/06/64	30/06/65	30/06/66	30/06/67	30/06/68	30/06/69	30/06/70	30/06/71	30/06/72
End Date	01/07/54	01/07/55	30/06/56	01/07/57	01/07/58	01/07/59	30/06/60	01/07/61	01/07/62	01/07/63	30/06/64	01/07/65	01/07/66	01/07/67	30/06/68	01/07/69	01/07/70	02/07/71	30/06/72	01/07/73
TIDAL PLANES (m)																				
H.H.W.S.S.	1.903	1.911	1.963	1.923	1.934	1.894	1.894	1.889	1.891	1.903	1.922	1.951	1.927	1.884	1.941	1.908	1.908	1.910	1.910	1.923
M.H.W.S.	1.557	1.568	1.620	1.582	1.593	1.552	1.555	1.546	1.549	1.559	1.582	1.602	1.578	1.539	1.597	1.561	1.563	1.563	1.565	1.580
M.H.W.	1.430	1.441	1.493	1.457	1.467	1.428	1.430	1.419	1.423	1.431	1.456	1.475	1.451	1.411	1.469	1.433	1.435	1.436	1.439	1.455
M.H.W.N.	1.302	1.314	1.366	1.331	1.342	1.303	1.305	1.293	1.296	1.304	1.330	1.348	1.324	1.282	1.341	1.304	1.307	1.308	1.313	1.330
M.S.L.	0.912	0.925	0.976	0.945	0.955	0.920	0.920	0.913	0.919	0.926	0.945	0.957	0.933	0.895	0.957	0.917	0.922	0.927	0.929	0.944
M.L.W.N.	0.522	0.536	0.585	0.559	0.569	0.536	0.535	0.534	0.541	0.548	0.559	0.565	0.543	0.509	0.573	0.531	0.537	0.546	0.545	0.558
M.L.W.	0.394	0.408	0.458	0.433	0.444	0.412	0.410	0.407	0.415	0.420	0.433	0.438	0.415	0.380	0.445	0.402	0.408	0.419	0.419	0.433
M.L.W.S.	0.267	0.281	0.332	0.308	0.318	0.287	0.285	0.281	0.289	0.293	0.307	0.311	0.288	0.251	0.318	0.273	0.280	0.291	0.293	0.308
I.S.L.W.	0.020	0.036	0.086	0.065	0.075	0.043	0.043	0.036	0.044	0.047	0.064	0.062	0.040	0.005	0.072	0.025	0.034	0.043	0.047	0.063
TIDAL RANGES (m)																				
M.N.R. (MHWN-MLWN)	0.780	0.778	0.781	0.772	0.773	0.767	0.769	0.759	0.755	0.756	0.770	0.783	0.782	0.773	0.768	0.773	0.770	0.762	0.769	0.772
M.R. (MHW-MLW)	1.035	1.032	1.035	1.023	1.024	1.016	1.020	1.012	1.008	1.011	1.023	1.037	1.036	1.030	1.024	1.031	1.026	1.017	1.020	1.022
M.S.R. (MHWS-MLWS)	1.290	1.287	1.288	1.274	1.275	1.265	1.270	1.264	1.260	1.266	1.275	1.291	1.290	1.288	1.280	1.288	1.283	1.272	1.272	1.272
R. (HHWSS-ISLW)	1.883	1.875	1.877	1.859	1.859	1.851	1.852	1.853	1.847	1.856	1.858	1.889	1.887	1.879	1.868	1.883	1.874	1.867	1.863	1.860
TIDAL CONSTITUENTS (m)																				
M2	0.518	0.516	0.517	0.512	0.512	0.508	0.510	0.506	0.504	0.505	0.511	0.519	0.518	0.515	0.512	0.515	0.513	0.509	0.510	0.511
S2	0.128	0.127	0.127	0.125	0.125	0.125	0.125	0.126	0.126	0.128	0.126	0.127	0.127	0.129	0.128	0.129	0.128	0.128	0.126	0.125
K1	0.150	0.149	0.149	0.148	0.148	0.148	0.147	0.148	0.148	0.148	0.147	0.149	0.150	0.150	0.149	0.151	0.149	0.151	0.150	0.147
O1	0.097	0.096	0.096	0.095	0.096	0.096	0.095	0.097	0.096	0.098	0.096	0.100	0.099	0.096	0.096	0.097	0.097	0.096	0.096	0.097
MSF	0.008	0.022	0.014	0.010	0.004	0.007	0.005	0.004	0.007	0.009	0.018	0.014	0.026	0.009	0.016	0.010	0.016	0.004	0.007	0.007
TIDAL CONSTITUENTS (deg)																				
M2	238.87	239.65	239.47	238.14	238.81	238.86	239.36	239.61	240.08	239.27	238.44	236.85	235.96	236.62	237.44	236.93	237.52	238.35	236.96	235.43
S2	262.55	263.97	264.05	262.39	262.18	261.92	262.77	263.20	263.50	263.29	262.79	261.15	261.24	261.58	261.92	262.14	261.48	262.60	260.86	260.55
K1	119.55	120.16	120.53	120.42	120.26	120.00	120.89	120.00	120.13	120.02	119.93	119.93	119.55	119.21	119.98	119.09	118.51	118.47	119.36	117.95
O1	80.78	80.99	80.69	80.22	80.28	79.74	79.37	81.29	81.58	80.38	81.55	79.96	79.53	79.81	79.89	80.13	81.10	80.04	80.65	79.75
MSF	148.77	256.60	329.93	218.13	179.20	97.95	60.23	343.75	133.47	236.60	329.99	214.98	247.73	159.04	300.67	31.21	333.66	239.37	311.09	118.12
RMS RESIDUAL ERROR (m)																				
	0.086	0.070	0.084	0.082	0.080	0.077	0.094	0.079	0.074	0.069	0.084	0.085	0.073	0.068	0.073	0.081	0.076	0.074	0.082	0.083
DATA CAPTURE (%)																				
	100.0%	99.2%	99.2%	100.0%	99.2%	100.0%	100.0%	100.0%	100.0%	99.6%	99.6%	100.0%	99.6%	98.8%	99.6%	98.0%	98.4%	98.0%	98.0%	100.0%

Table B2 Tidal planes analysis – Fort Denison (continued)

Classification	Onshore Bay or Port
Datum	Zero Fort Denison
Period of Analysis	01/06/1914-30/06/2016

Start Date	30/06/73	30/06/74	30/06/75	30/06/76	30/06/77	30/06/78	30/06/79	30/06/80	30/06/81	30/06/82	30/06/83	30/06/84	30/06/85	30/06/86	30/06/87	30/06/88	30/06/89	30/06/90	30/06/91	30/06/92
End Date	01/07/74	01/07/75	30/06/76	01/07/77	01/07/78	01/07/79	30/06/80	01/07/81	01/07/82	01/07/83	30/06/84	01/07/85	01/07/86	01/07/87	30/06/88	01/07/89	01/07/90	01/07/91	30/06/92	01/07/93
TIDAL PLANES (m)																				
H.H.W.S.S.	1.946	1.957	1.941	1.978	1.936	1.935	1.923	1.941	1.929	1.895	1.933	1.941	1.949	1.898	1.904	1.947	1.960	1.946	1.912	1.909
M.H.W.S.	1.602	1.611	1.595	1.635	1.588	1.583	1.571	1.592	1.577	1.544	1.578	1.593	1.600	1.557	1.565	1.604	1.617	1.606	1.573	1.568
M.H.W.	1.478	1.486	1.470	1.509	1.463	1.457	1.446	1.467	1.450	1.419	1.449	1.464	1.473	1.432	1.439	1.478	1.491	1.481	1.449	1.445
M.H.W.N.	1.354	1.362	1.345	1.384	1.338	1.332	1.321	1.342	1.323	1.293	1.321	1.336	1.345	1.308	1.312	1.351	1.366	1.357	1.325	1.321
M.S.L.	0.969	0.979	0.964	0.997	0.950	0.939	0.933	0.954	0.942	0.904	0.933	0.958	0.964	0.929	0.939	0.980	0.994	0.982	0.948	0.944
M.L.W.N.	0.584	0.595	0.584	0.610	0.562	0.546	0.544	0.566	0.560	0.514	0.545	0.580	0.584	0.550	0.567	0.609	0.622	0.607	0.571	0.566
M.L.W.	0.460	0.471	0.459	0.484	0.437	0.420	0.419	0.441	0.434	0.388	0.416	0.451	0.456	0.425	0.440	0.483	0.496	0.483	0.447	0.442
M.L.W.S.	0.336	0.346	0.334	0.358	0.312	0.295	0.295	0.316	0.307	0.263	0.288	0.323	0.328	0.300	0.314	0.356	0.371	0.359	0.323	0.319
I.S.L.W.	0.090	0.099	0.087	0.113	0.064	0.043	0.043	0.066	0.055	0.012	0.034	0.074	0.079	0.056	0.071	0.112	0.125	0.116	0.081	0.075
TIDAL RANGES (m)																				
M.N.R. (MHWN-MLWN)	0.769	0.767	0.761	0.774	0.777	0.786	0.777	0.776	0.763	0.779	0.776	0.756	0.761	0.758	0.746	0.742	0.744	0.750	0.754	0.756
M.R. (MHW-MLW)	1.017	1.016	1.011	1.025	1.026	1.037	1.027	1.026	1.017	1.030	1.033	1.013	1.017	1.008	0.999	0.995	0.995	0.998	1.002	1.002
M.S.R. (MHWS-MLWS)	1.265	1.264	1.261	1.277	1.275	1.289	1.276	1.276	1.270	1.281	1.291	1.270	1.272	1.257	1.251	1.248	1.246	1.247	1.251	1.249
R. (HHWSS-ISLW)	1.856	1.859	1.855	1.865	1.872	1.891	1.880	1.875	1.874	1.883	1.899	1.867	1.869	1.842	1.833	1.835	1.835	1.831	1.831	1.834
TIDAL CONSTITUENTS (m)																				
M2	0.509	0.508	0.506	0.513	0.513	0.519	0.513	0.513	0.508	0.515	0.517	0.507	0.508	0.504	0.499	0.498	0.498	0.499	0.501	0.501
S2	0.124	0.124	0.125	0.126	0.125	0.126	0.125	0.125	0.127	0.125	0.129	0.128	0.128	0.125	0.126	0.126	0.125	0.124	0.124	0.123
K1	0.150	0.149	0.149	0.149	0.152	0.152	0.151	0.151	0.152	0.151	0.153	0.151	0.151	0.148	0.148	0.149	0.148	0.147	0.146	0.148
O1	0.096	0.099	0.099	0.096	0.097	0.099	0.101	0.099	0.099	0.100	0.100	0.098	0.098	0.096	0.095	0.096	0.097	0.096	0.095	0.096
MSF	0.013	0.010	0.011	0.015	0.013	0.009	0.005	0.013	0.003	0.007	0.017	0.017	0.022	0.010	0.005	0.015	0.005	0.006	0.005	0.020
TIDAL CONSTITUENTS (deg)																				
M2	235.87	238.09	237.57	238.17	237.71	239.22	239.31	239.21	239.68	239.06	239.04	238.52	238.51	237.63	237.34	238.20	237.90	236.91	236.13	236.19
S2	259.68	262.49	262.53	262.57	262.51	263.47	262.81	262.27	262.60	263.66	262.16	261.54	261.54	261.57	261.34	261.49	260.95	261.06	261.45	260.12
K1	119.20	120.81	119.91	120.28	120.83	120.45	120.90	120.64	120.42	120.68	120.65	120.65	120.23	120.08	119.65	120.08	120.11	119.23	119.61	118.25
O1	78.60	80.16	77.66	81.38	79.23	80.93	79.86	79.46	80.13	79.84	79.89	78.97	80.60	79.87	79.68	80.36	79.56	79.02	78.58	77.82
MSF	144.74	8.50	188.38	357.77	229.51	77.25	176.19	178.53	54.44	178.07	289.88	56.23	303.21	106.00	137.61	210.37	277.44	333.44	346.54	53.42
RMS RESIDUAL ERROR (m)																				
	0.112	0.083	0.084	0.078	0.088	0.081	0.077	0.081	0.073	0.074	0.073	0.083	0.077	0.065	0.082	0.076	0.087	0.084	0.066	0.073
DATA CAPTURE (%)																				
	98.8%	98.4%	96.8%	96.8%	98.4%	100.0%	100.0%	98.4%	95.6%	98.0%	99.6%	98.8%	98.0%	97.6%	99.6%	99.2%	99.6%	98.8%	99.2%	95.6%

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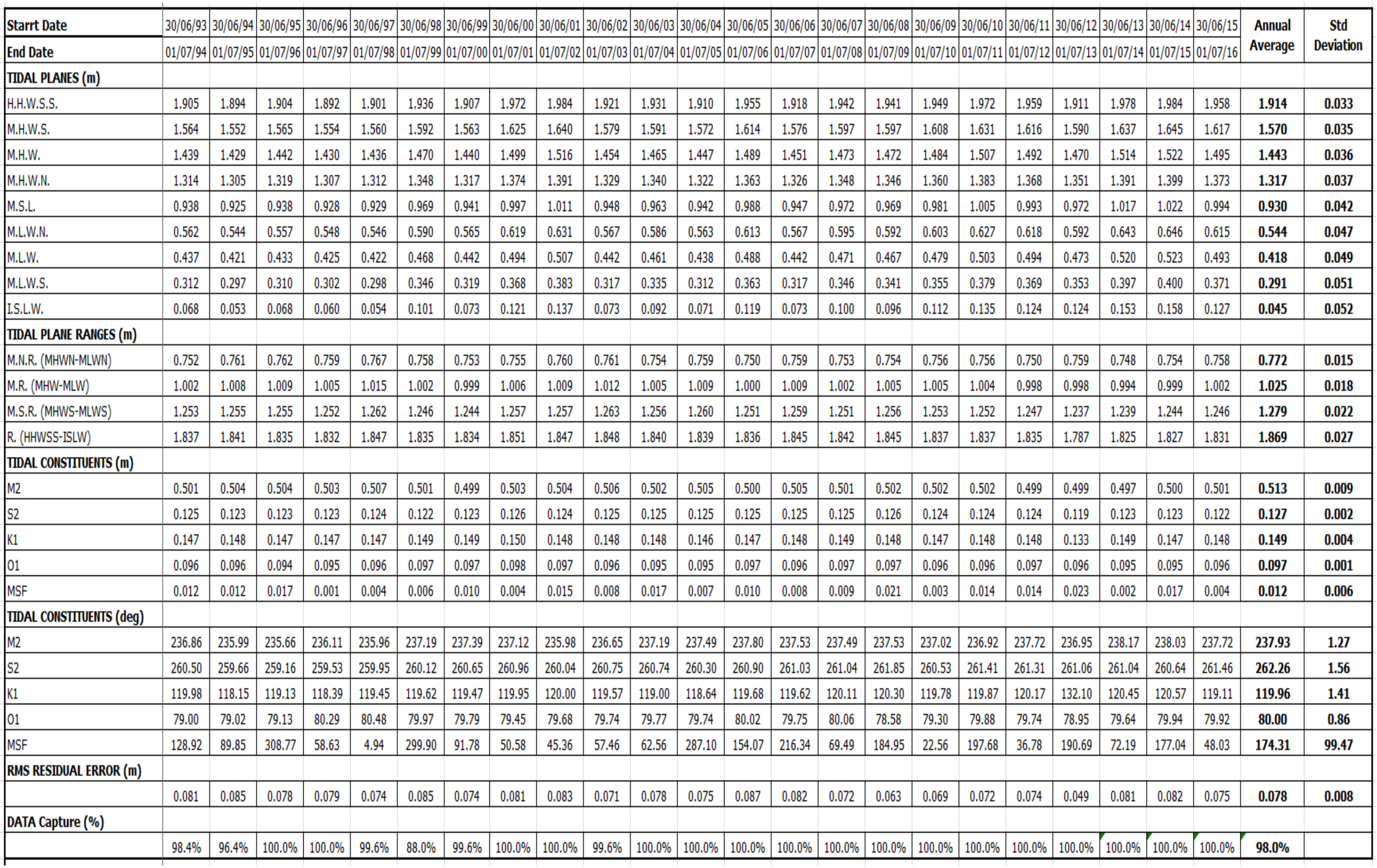
Table B2 Tidal planes analysis – Fort Denison (continued)

Classification	Onshore Bay or Port
Datum	Zero Fort Denison Tide
Period of Analysis	01/06/1914-30/06/2016



Starrt Date	30/06/93	30/06/94	30/06/95	30/06/96	30/06/97	30/06/98	30/06/99	30/06/00	30/06/01	30/06/02	30/06/03	30/06/04	30/06/05	30/06/06	30/06/07	30/06/08	30/06/09	30/06/10	30/06/11	30/06/12	30/06/13	30/06/14	30/06/15	Annual Average	Std Deviation
End Date	01/07/94	01/07/95	01/07/96	01/07/97	01/07/98	01/07/99	01/07/00	01/07/01	01/07/02	01/07/03	01/07/04	01/07/05	01/07/06	01/07/07	01/07/08	01/07/09	01/07/10	01/07/11	01/07/12	01/07/13	01/07/14	01/07/15	01/07/16		
TIDAL PLANES (m)																									
H.H.W.S.S.	1.905	1.894	1.904	1.892	1.901	1.936	1.907	1.972	1.984	1.921	1.931	1.910	1.955	1.918	1.942	1.941	1.949	1.972	1.959	1.911	1.978	1.984	1.958	**1.914**	**0.033**
M.H.W.S.	1.564	1.552	1.565	1.554	1.560	1.592	1.563	1.625	1.640	1.579	1.591	1.572	1.614	1.576	1.597	1.597	1.608	1.631	1.616	1.590	1.637	1.645	1.617	**1.570**	**0.035**
M.H.W.	1.439	1.429	1.442	1.430	1.436	1.470	1.440	1.499	1.516	1.454	1.465	1.447	1.489	1.451	1.473	1.472	1.484	1.507	1.492	1.470	1.514	1.522	1.495	**1.443**	**0.036**
M.H.W.N.	1.314	1.305	1.319	1.307	1.312	1.348	1.317	1.374	1.391	1.329	1.340	1.322	1.363	1.326	1.348	1.346	1.360	1.383	1.368	1.351	1.391	1.399	1.373	**1.317**	**0.037**
M.S.L.	0.938	0.925	0.938	0.928	0.929	0.969	0.941	0.997	1.011	0.948	0.963	0.942	0.988	0.947	0.972	0.969	0.981	1.005	0.993	0.972	1.017	1.022	0.994	**0.930**	**0.042**
M.L.W.N.	0.562	0.544	0.557	0.548	0.546	0.590	0.565	0.619	0.631	0.567	0.586	0.563	0.613	0.567	0.595	0.592	0.603	0.627	0.618	0.592	0.643	0.646	0.615	**0.544**	**0.047**
M.L.W.	0.437	0.421	0.433	0.425	0.422	0.468	0.442	0.494	0.507	0.442	0.461	0.438	0.488	0.442	0.471	0.467	0.479	0.503	0.494	0.473	0.520	0.523	0.493	**0.418**	**0.049**
M.L.W.S.	0.312	0.297	0.310	0.302	0.298	0.346	0.319	0.368	0.383	0.317	0.335	0.312	0.363	0.317	0.346	0.341	0.355	0.379	0.369	0.353	0.397	0.400	0.371	**0.291**	**0.051**
I.S.L.W.	0.068	0.053	0.068	0.060	0.054	0.101	0.073	0.121	0.137	0.073	0.092	0.071	0.119	0.073	0.100	0.096	0.112	0.135	0.124	0.124	0.153	0.158	0.127	**0.045**	**0.052**
TIDAL PLANE RANGES (m)																									
M.N.R. (MHWN-MLWN)	0.752	0.761	0.762	0.759	0.767	0.758	0.753	0.755	0.760	0.761	0.754	0.759	0.750	0.759	0.753	0.754	0.756	0.756	0.750	0.759	0.748	0.754	0.758	**0.772**	**0.015**
M.R. (MHW-MLW)	1.002	1.008	1.009	1.005	1.015	1.002	0.999	1.006	1.009	1.012	1.005	1.009	1.000	1.009	1.002	1.005	1.005	1.004	0.998	0.998	0.994	0.999	1.002	**1.025**	**0.018**
M.S.R. (MHWS-MLWS)	1.253	1.255	1.255	1.252	1.262	1.246	1.244	1.257	1.257	1.263	1.256	1.260	1.251	1.259	1.251	1.256	1.253	1.252	1.247	1.237	1.239	1.244	1.246	**1.279**	**0.022**
R. (HHWSS-ISLW)	1.837	1.841	1.835	1.832	1.847	1.835	1.834	1.851	1.847	1.848	1.840	1.839	1.836	1.845	1.842	1.845	1.837	1.837	1.835	1.787	1.825	1.827	1.831	**1.869**	**0.027**
TIDAL CONSTITUENTS (m)																									
M2	0.501	0.504	0.504	0.503	0.507	0.501	0.499	0.503	0.504	0.506	0.502	0.505	0.500	0.505	0.501	0.502	0.502	0.502	0.499	0.499	0.497	0.500	0.501	**0.513**	**0.009**
S2	0.125	0.123	0.123	0.123	0.124	0.122	0.123	0.126	0.124	0.125	0.125	0.125	0.125	0.125	0.125	0.126	0.124	0.124	0.124	0.119	0.123	0.123	0.122	**0.127**	**0.002**
K1	0.147	0.148	0.147	0.147	0.147	0.149	0.149	0.150	0.148	0.148	0.148	0.146	0.147	0.148	0.149	0.148	0.147	0.148	0.148	0.133	0.149	0.147	0.148	**0.149**	**0.004**
O1	0.096	0.096	0.094	0.095	0.096	0.097	0.097	0.098	0.097	0.096	0.095	0.095	0.097	0.096	0.097	0.097	0.096	0.096	0.097	0.096	0.095	0.095	0.096	**0.097**	**0.001**
MSF	0.012	0.012	0.017	0.001	0.004	0.006	0.010	0.004	0.015	0.008	0.017	0.007	0.010	0.008	0.009	0.021	0.003	0.014	0.014	0.023	0.002	0.017	0.004	**0.012**	**0.006**
TIDAL CONSTITUENTS (deg)																									
M2	236.86	235.99	235.66	236.11	235.96	237.19	237.39	237.12	235.98	236.65	237.19	237.49	237.80	237.53	237.49	237.53	237.02	236.92	237.72	236.95	238.17	238.03	237.72	**237.93**	**1.27**
S2	260.50	259.66	259.16	259.53	259.95	260.12	260.65	260.96	260.04	260.75	260.74	260.30	260.90	261.03	261.04	261.85	260.53	261.41	261.31	261.06	261.04	260.64	261.46	**262.26**	**1.56**
K1	119.98	118.15	119.13	118.39	119.45	119.62	119.47	119.95	120.00	119.57	119.00	118.64	119.68	119.62	120.11	120.30	119.78	119.87	120.17	132.10	120.45	120.57	119.11	**119.96**	**1.41**
O1	79.00	79.02	79.13	80.29	80.48	79.97	79.79	79.45	79.68	79.74	79.77	79.74	80.02	79.75	80.06	78.58	79.30	79.88	79.74	78.95	79.64	79.94	79.92	**80.00**	**0.86**
MSF	128.92	89.85	308.77	58.63	4.94	299.90	91.78	50.58	45.36	57.46	62.56	287.10	154.07	216.34	69.49	184.95	22.56	197.68	36.78	190.69	72.19	177.04	48.03	**174.31**	**99.47**
RMS RESIDUAL ERROR (m)																									
	0.081	0.085	0.078	0.079	0.074	0.085	0.074	0.081	0.083	0.071	0.078	0.075	0.087	0.082	0.072	0.063	0.069	0.072	0.074	0.049	0.081	0.082	0.075	**0.078**	**0.008**
DATA Capture (%)																									
	98.4%	96.4%	100.0%	100.0%	99.6%	88.0%	99.6%	100.0%	100.0%	99.6%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**98.0%**	

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Frequency distribution of measured water levels – Fort Denison

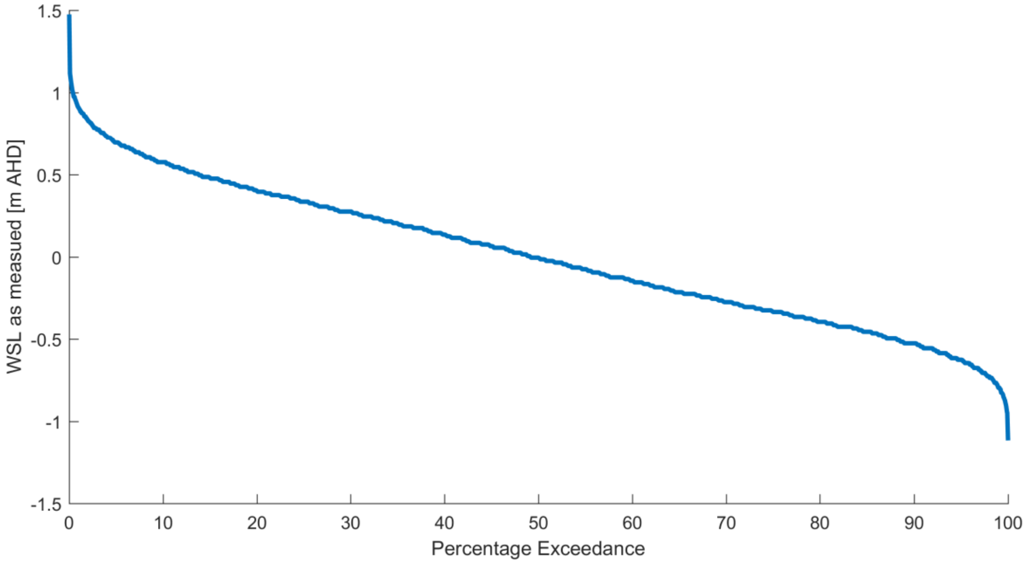

Figure B1.1 WSL exceedance without detrending

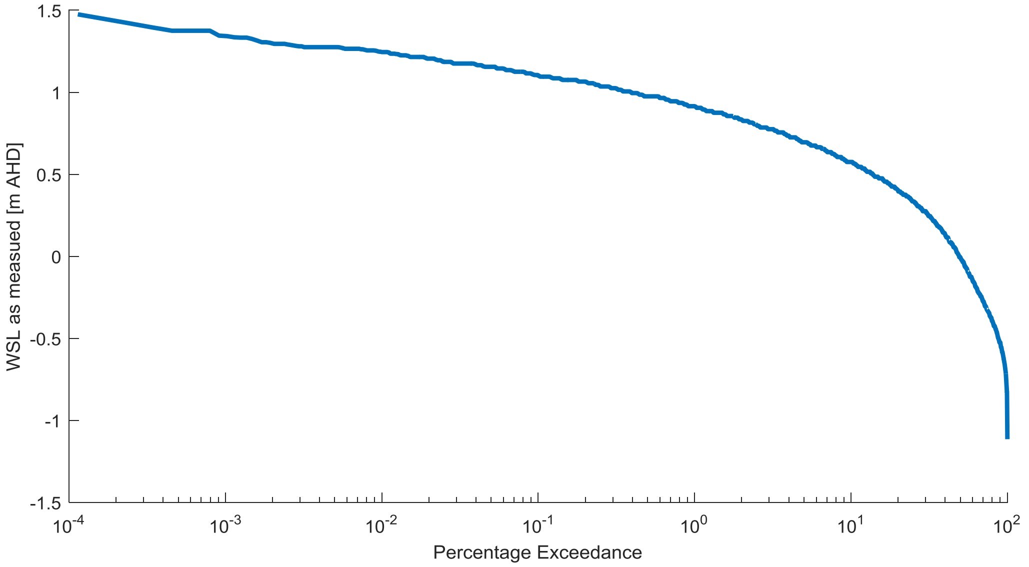

Figure B1.2 Log WSL exceedance without detrending

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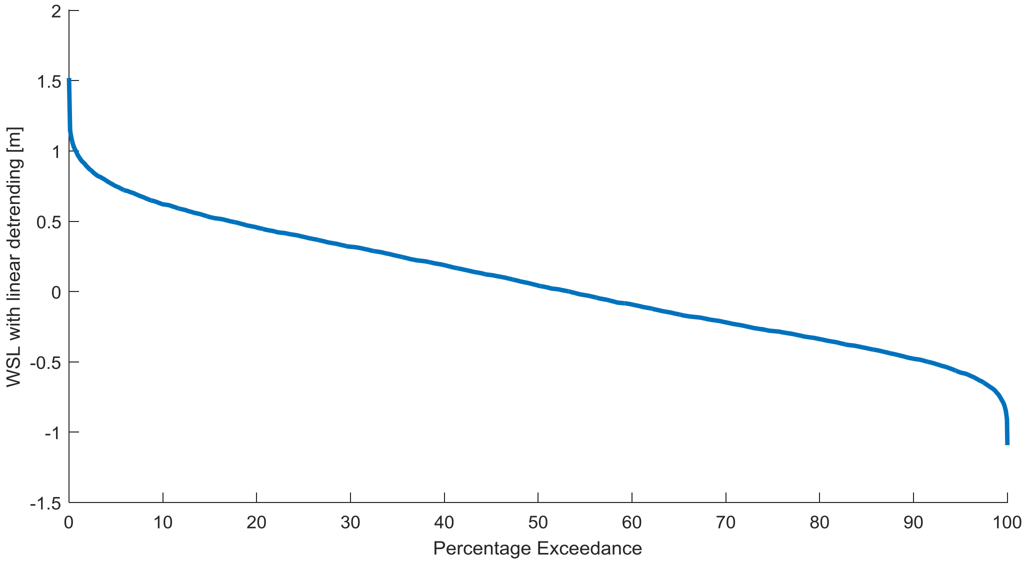

Figure B1.3 WSL exceedance with detrending

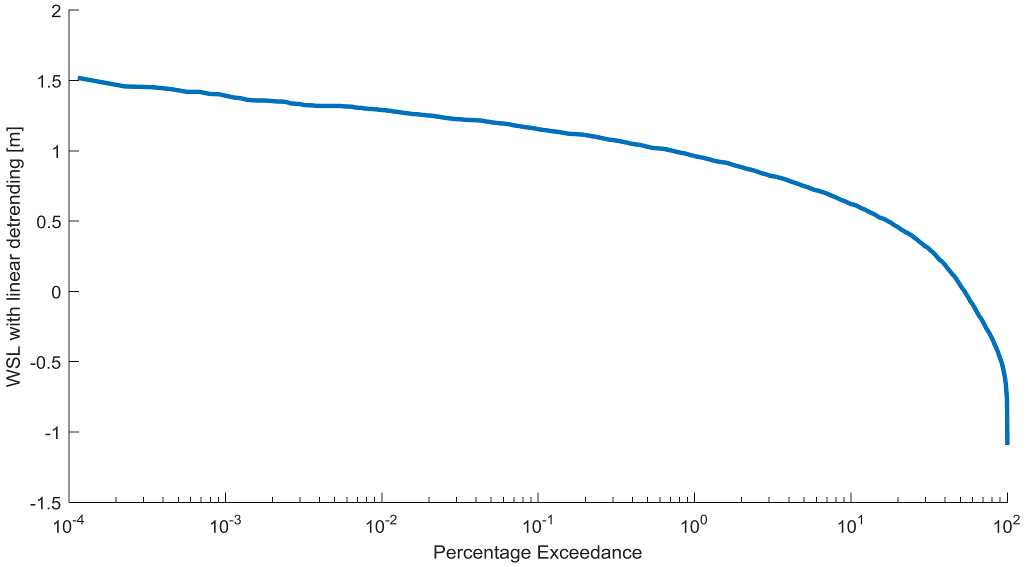

Figure B1.4 WSL exceedance with detrending

Frequency distribution of tidal residuals – Fort Denison

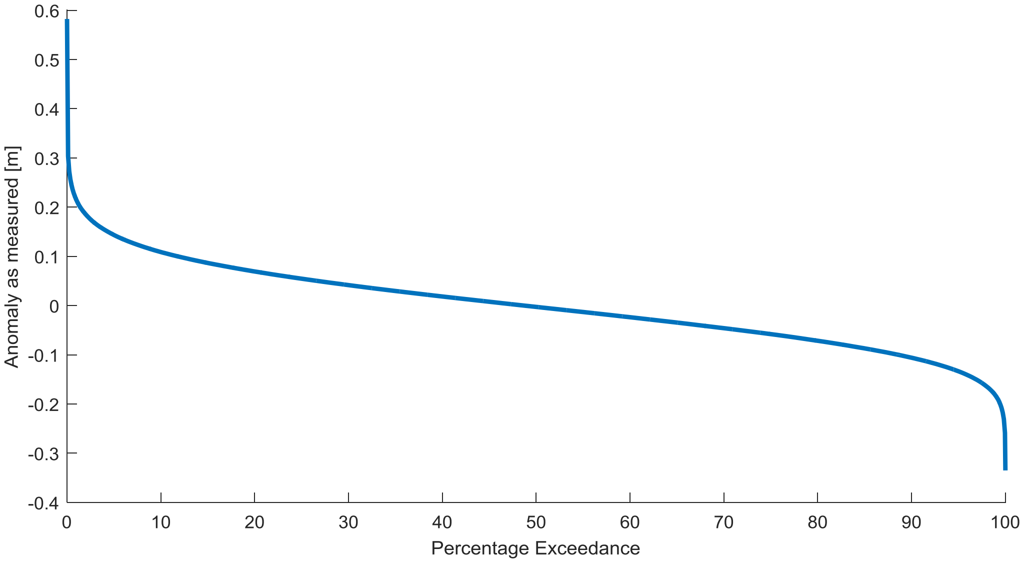

Figure B2.1 Anomaly exceedance without detrending

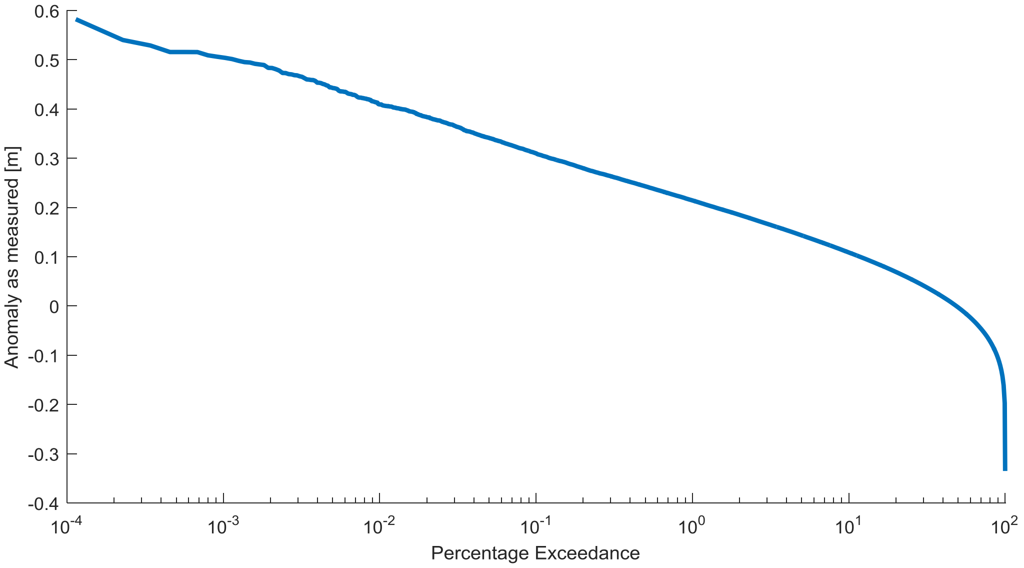

Figure B2.2 Log anomaly exceedance without detrending

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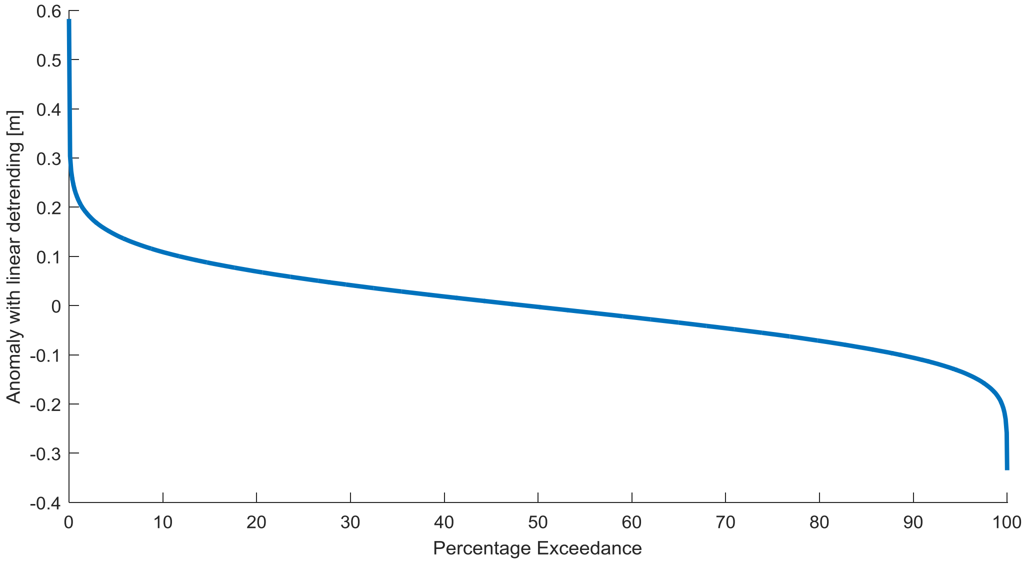

Figure B2.3 Anomaly exceedance with detrending

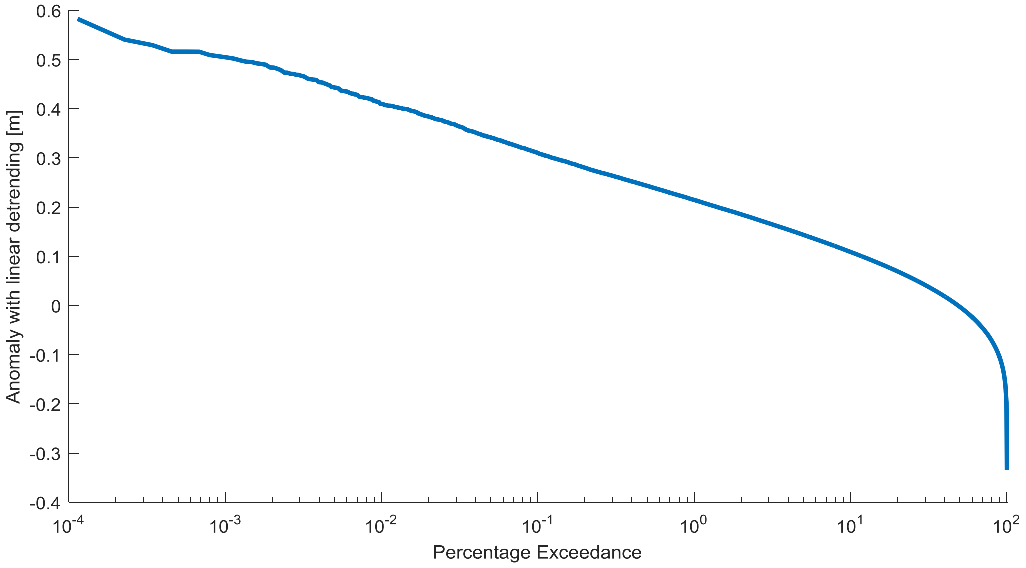

Figure B2.4 Log anomaly exceedance with detrending

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Appendix C. Extreme value analysis

Table C1 Coffs Harbour extreme value analysis

General Information	
Site Name	Coffs Harbour
Location	Coffs Harbour Boat Harbour
Period of Data	1996-Present
Period of Analysis	31/12/1996-30/06/2016
AWRC	205470
MGA Zone	56
Easting	514052
Northing	6647644
Datum	Coffs Port Datum
Adjustment to AHD (m)	-0.882
Classification	Onshore Bay or Port
Logger	CR800
Primary Sensor	Radar
Secondary Sensor	Vented Pressure

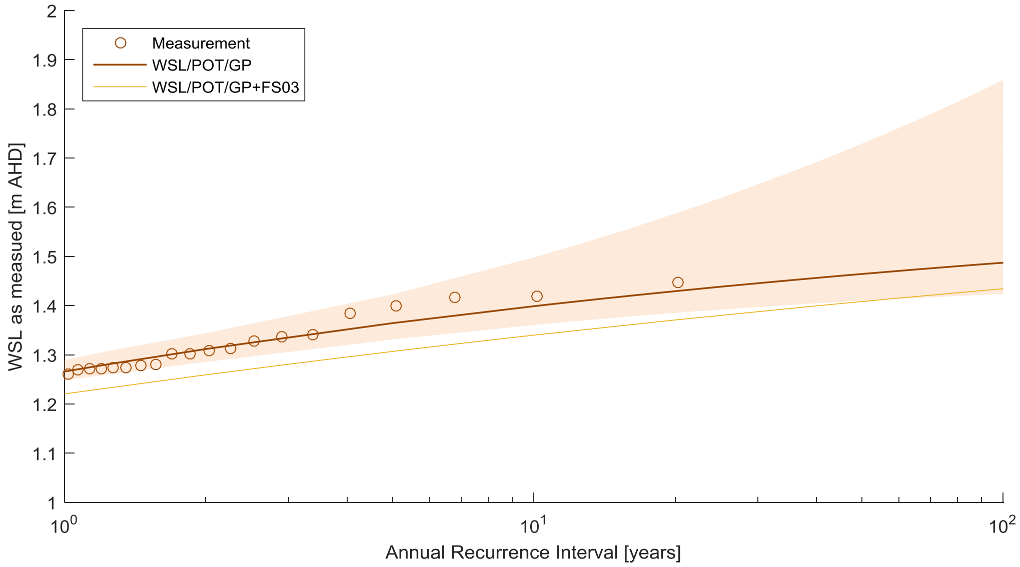

Figure C1.1 Extreme value analysis on WSL without detrending – Coffs Harbour

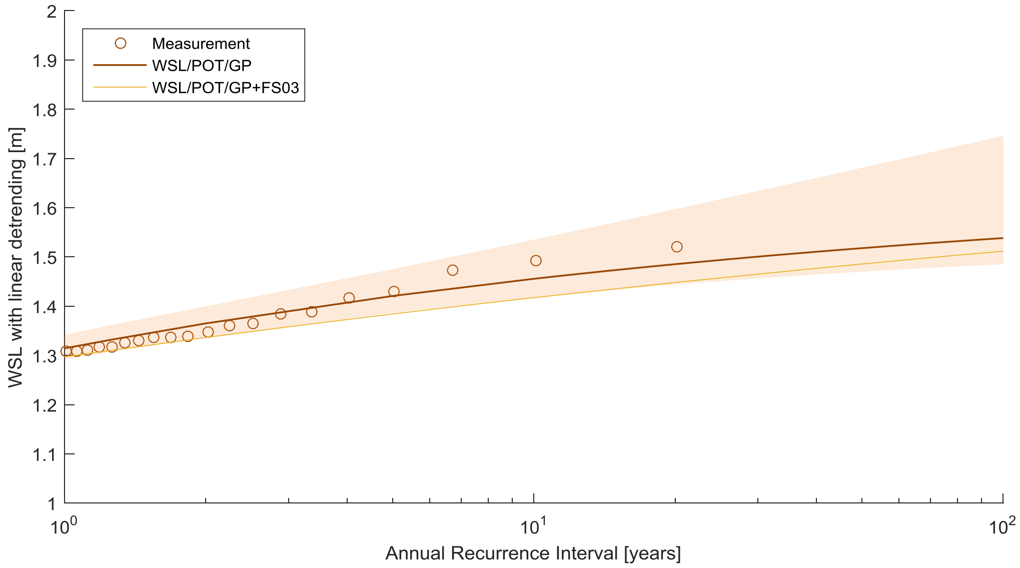

Figure C1.2 Extreme value analysis on WSL with detrending – Coffs Harbour

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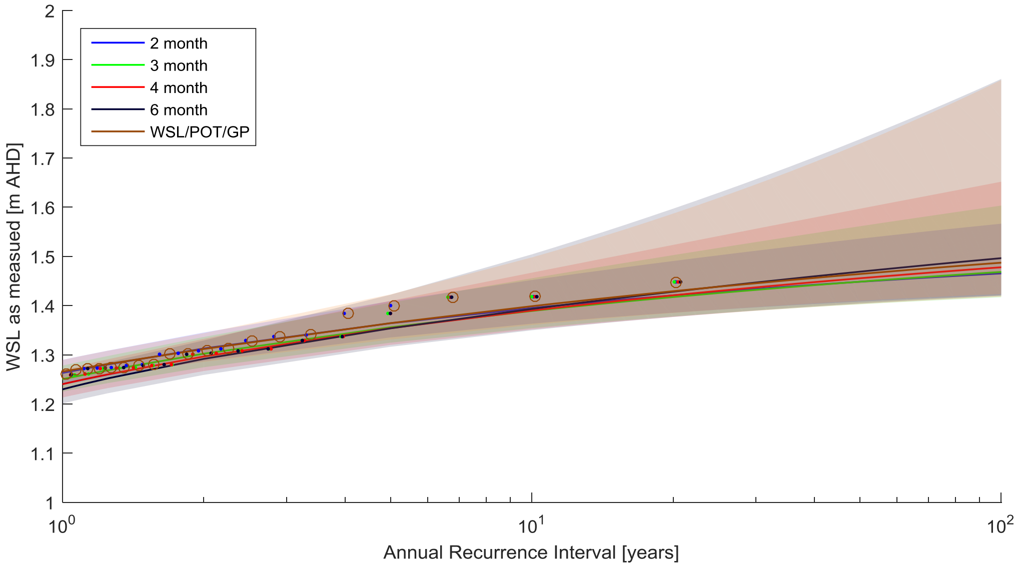

Figure C1.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Coffs Harbour

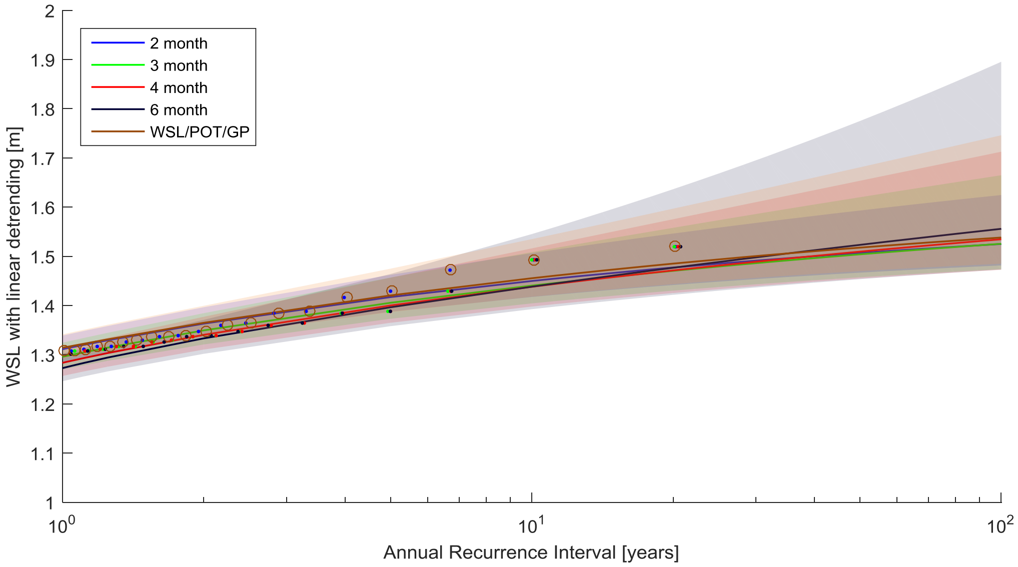

Figure C1.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Coffs Harbour

Table C2 Crowdy Head (combined) extreme value analysis

General information	
Site Name	Crowdy Head
Location	Crowdy Head Boat Harbour
Period of Data	1986-present
Period of Analysis	1/7/1986-30/06/2016
AWRC	208470
MGA Zone	56
Easting	476421.77 / 476346.21
Northing	6477356.50 / 6477415.08
Datum	Crowdy Head Datum
Adjustment to AHD (m)	-0.911
Classification	Onshore Bay or Port
Logger	CR800
Primary Sensor	Vented Pressure / Radar
Secondary Sensor	Vented Pressure

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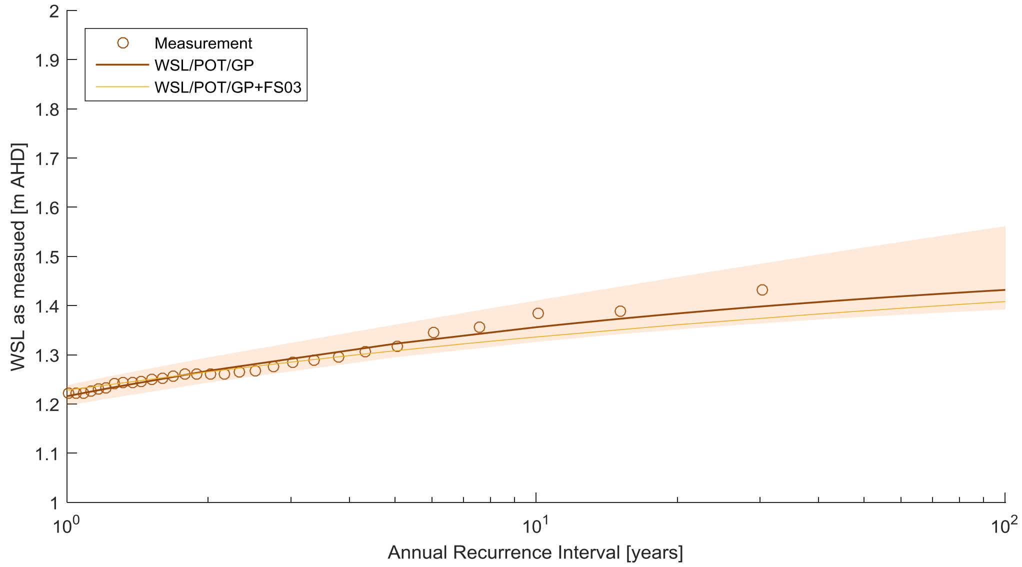

Figure C2.1 Extreme value analysis on WSL without detrending – Crowdy Head

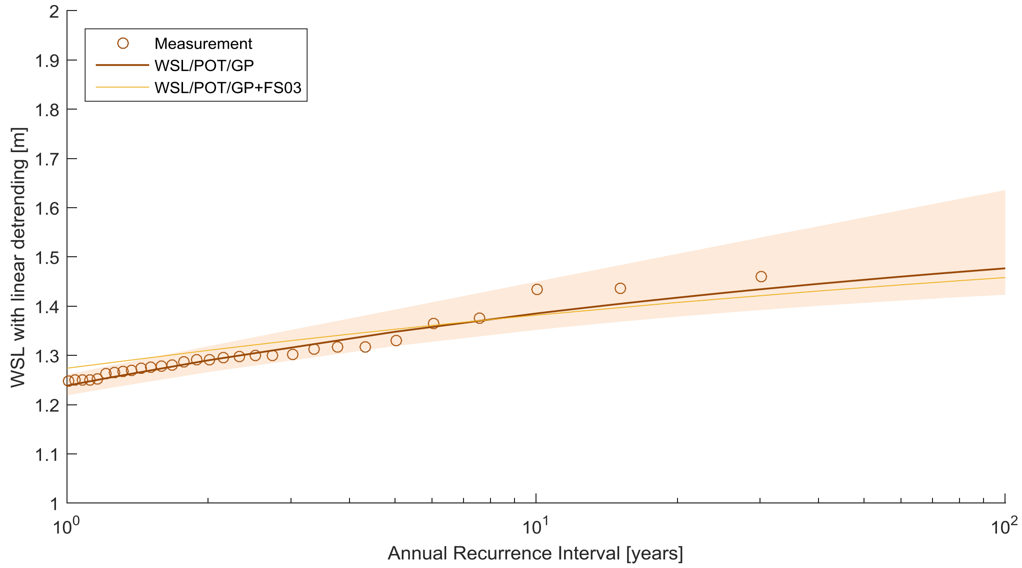

Figure C2.2 Extreme value analysis on WSL with detrending – Crowdy Head

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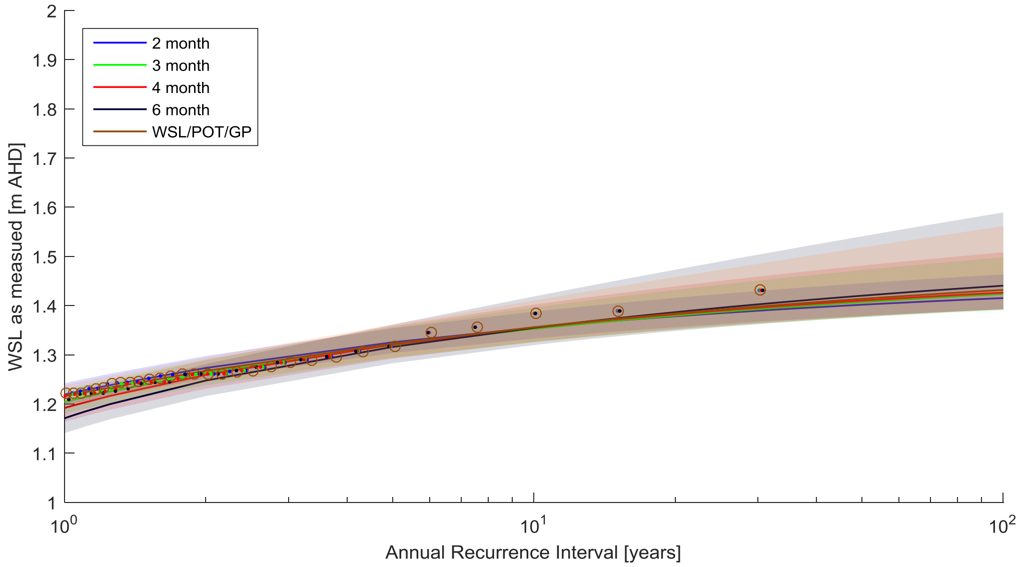

Figure C2.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Crowdy Head

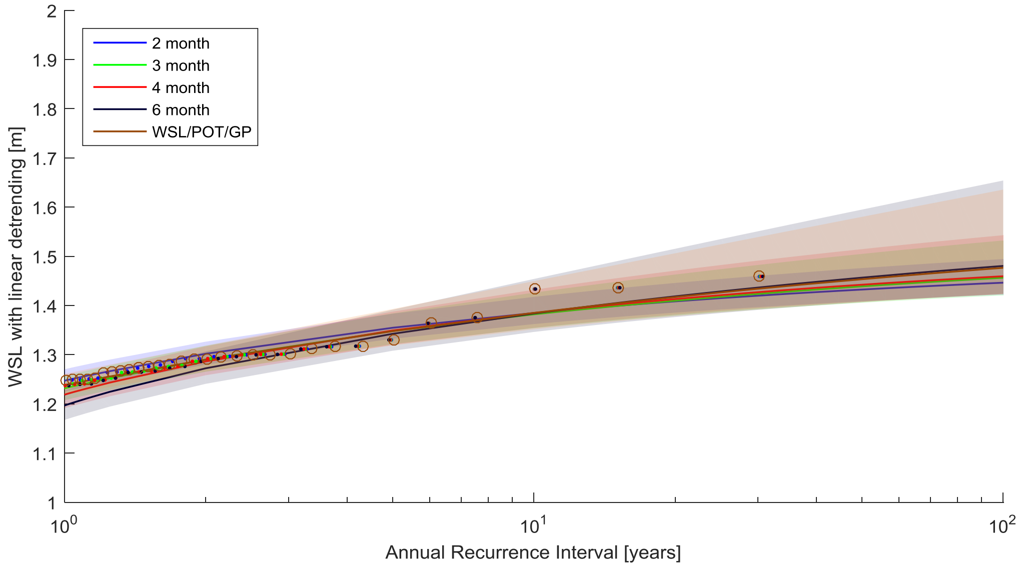

Figure C2.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Crowdy Head

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Table C3 Port Stephens (combined) extreme value analysis

General information	
Site Name	Tomaree / Shoal Bay
Location	Port Stephens
Period of Data	1985-Present
Period of Analysis	23/09/1985-30/06/2016
AWRC	209450
MGA Zone	56
Easting	423362.42 / 422748.94
Northing	6380025.11 / 6379489.15
Datum	Port Stephens Hydro Datum
Adjustment to AHD (m)	-0.944
Classification	Onshore Bay or Port
Logger	CR800 / CR1000
Primary Sensor	Radar
Secondary Sensor	Vented Pressure

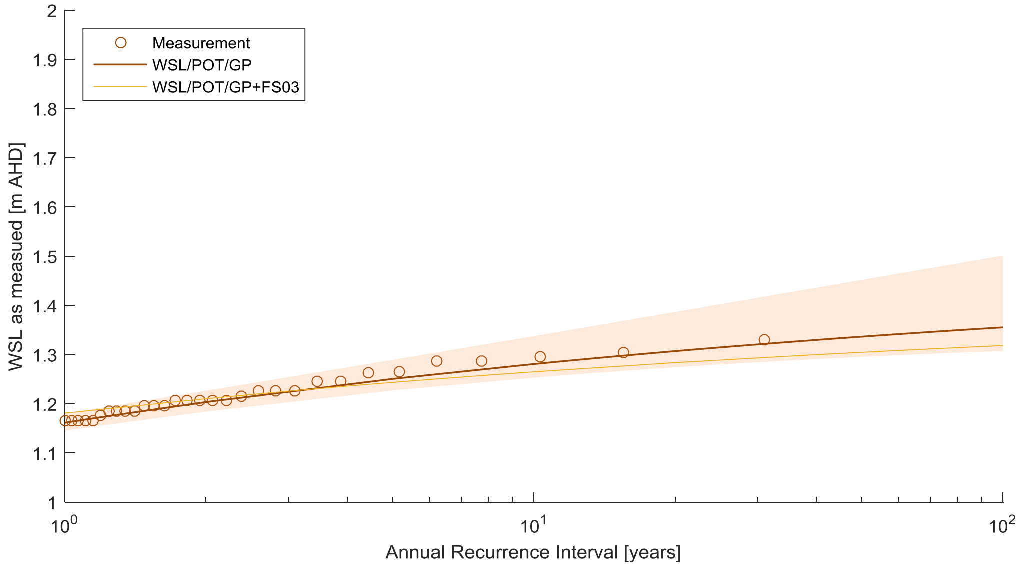

Figure C3.1 Extreme value analysis on WSL without detrending – Port Stephens

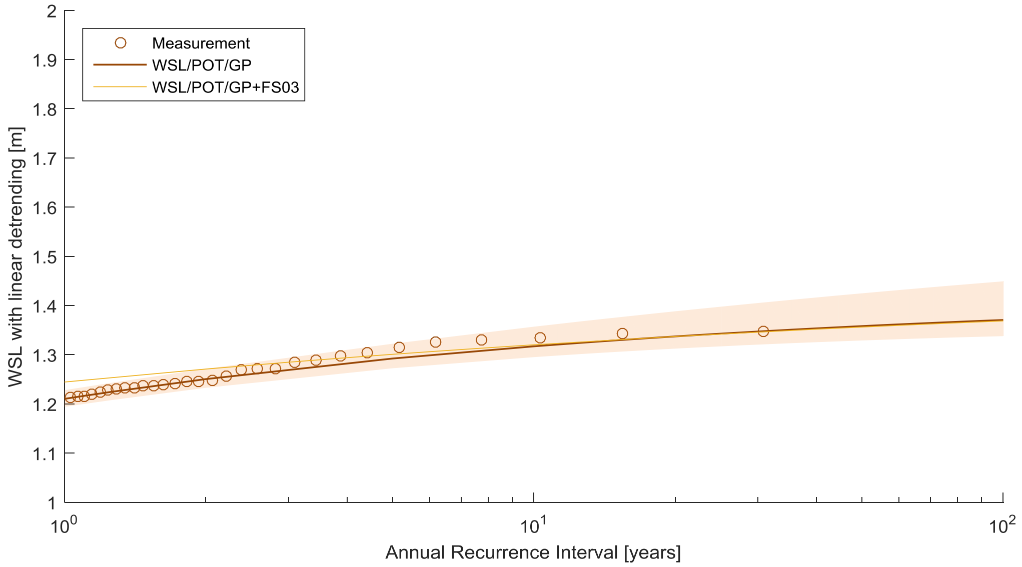

Figure C3.2 Extreme value analysis on WSL with detrending – Port Stephens

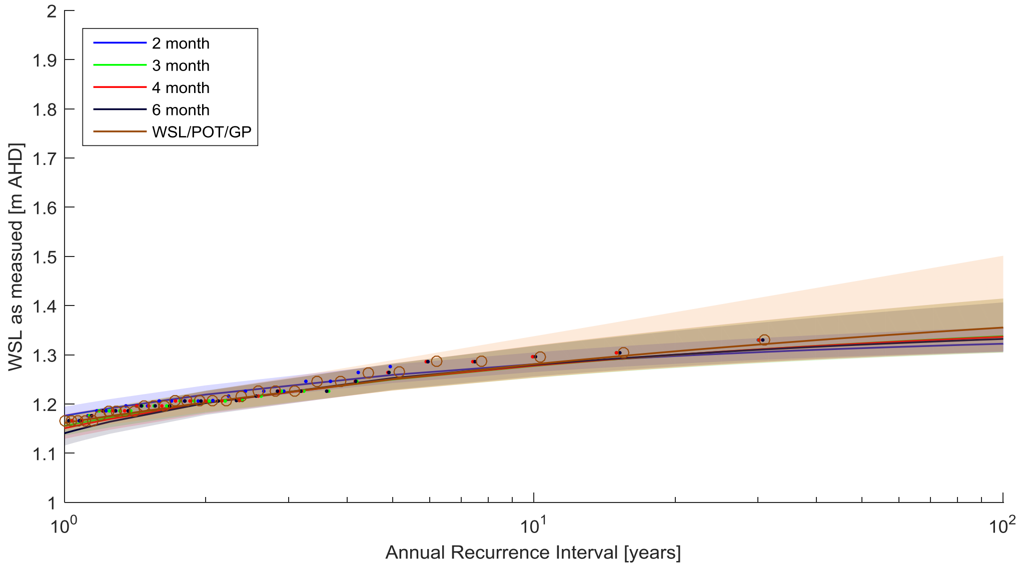

Figure C3.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Port Stephens

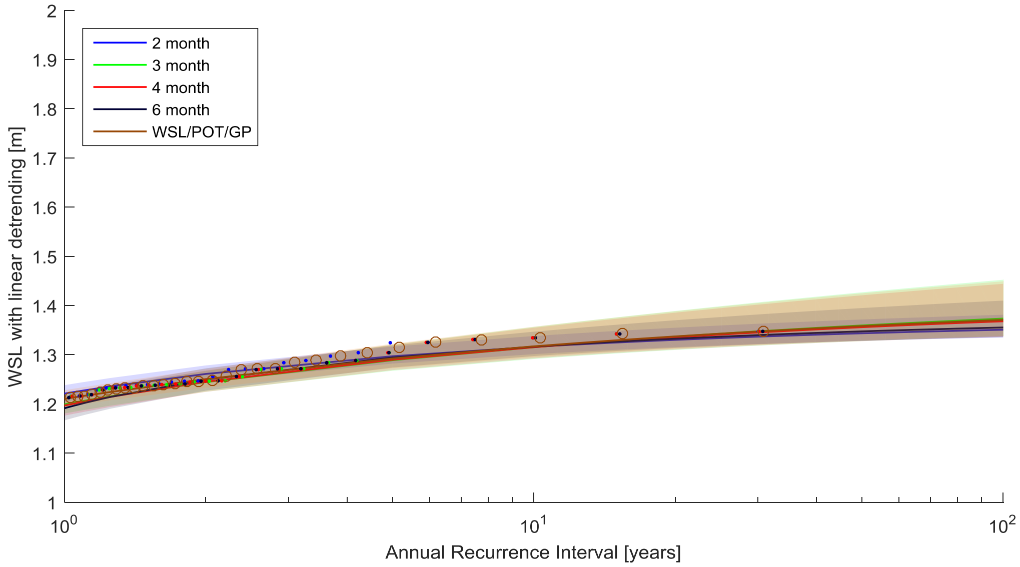

Figure C3.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Port Stephens

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Table C4 Patonga extreme value analysis

General information	
Site Name	Patonga
Location	Hawkesbury River
Period of Data	1992-Present
Period of Analysis	03/06/1992-30/06/2016
AWRC	212440
MGA Zone	56
Easting	339821.85
Northing	6286295.14
Datum	Australian Height Datum
Adjustment to AHD (m)	0.0
Classification	Onshore Bay or Port
Logger	CR800
Primary Sensor	Radar
Secondary Sensor	Vented Pressure

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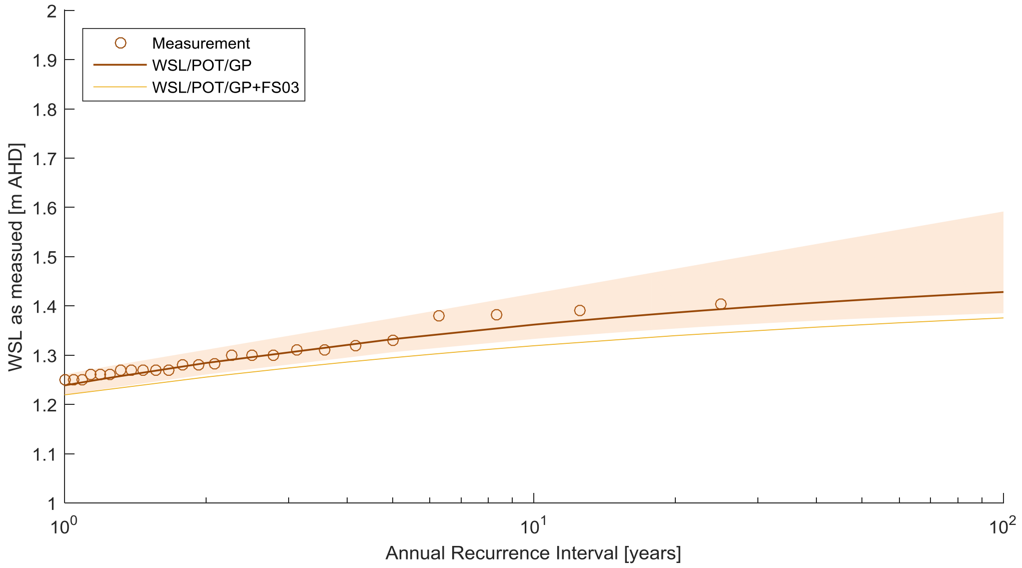

Figure C4.1 Extreme value analysis on WSL without detrending – Patonga

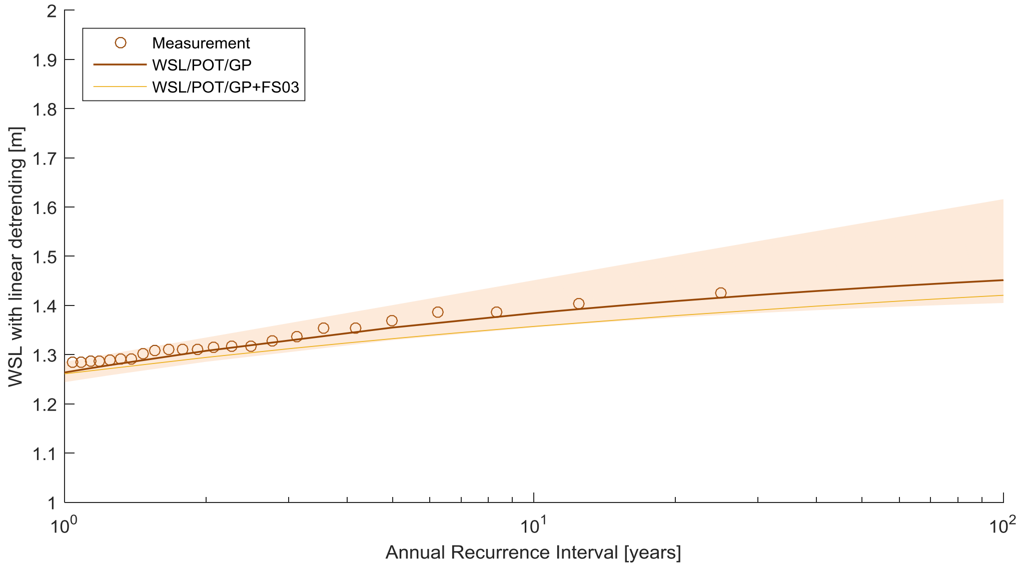

Figure C4.2 Extreme value analysis on WSL with detrending – Patonga

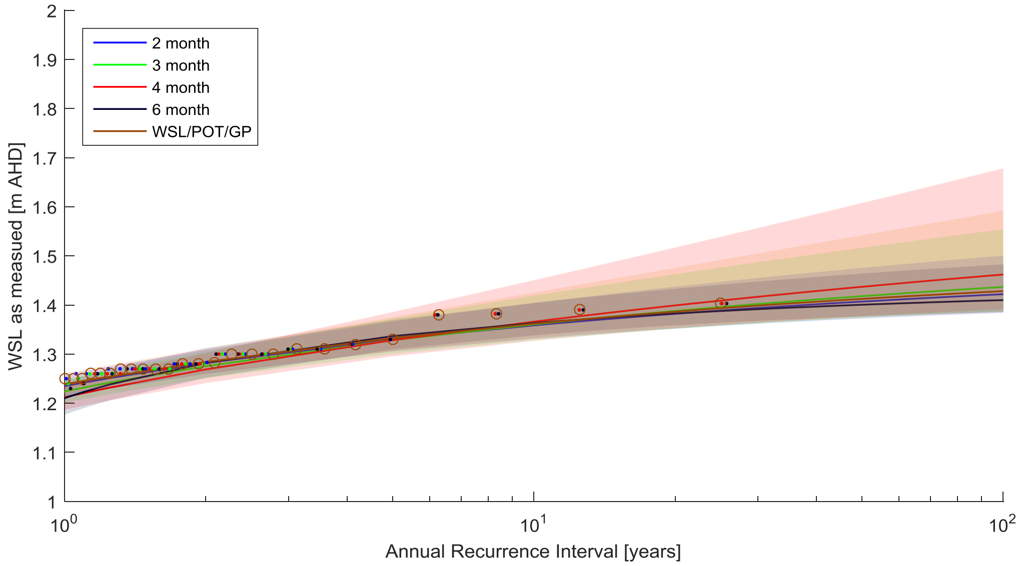

Figure C4.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Patonga

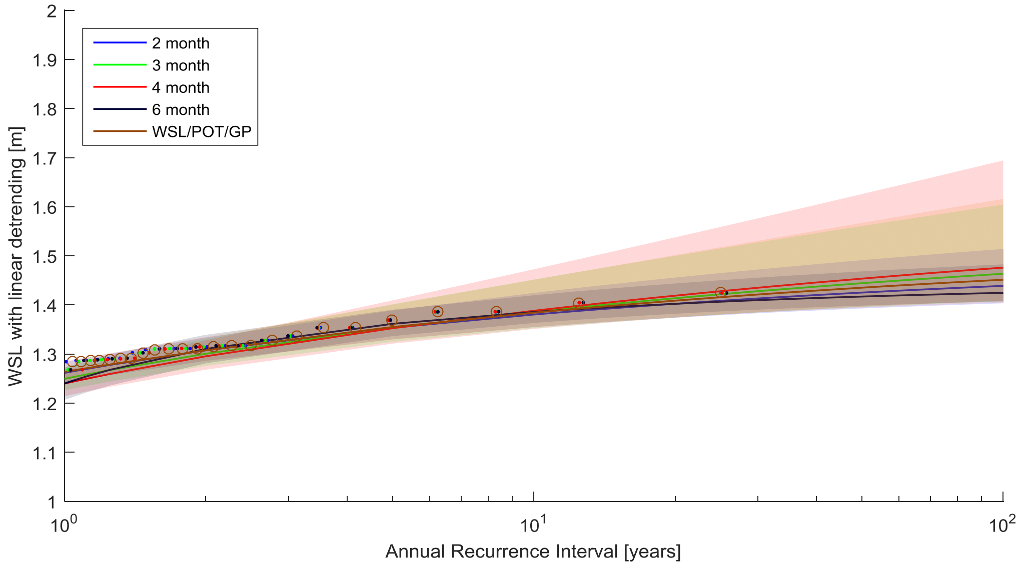

Figure C4.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Patonga

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Table C5 Fort Denison extreme value analysis

General information	
Site Name	Fort Denison
Location	Sydney Harbour
Period of Data	1914-Present
Period of Analysis	01/06/1914-01/01/2017
AWRC	60370
MGA Zone	56
Easting	335865.89
Northing	6252542.11
Datum	Zero Fort Denison Tide Gauge
Adjustment to AHD (m)	-0.925
Classification	Onshore Bay or Port
Logger	not available
Primary Sensor	Searanger sonic sensor
Secondary Sensor	none

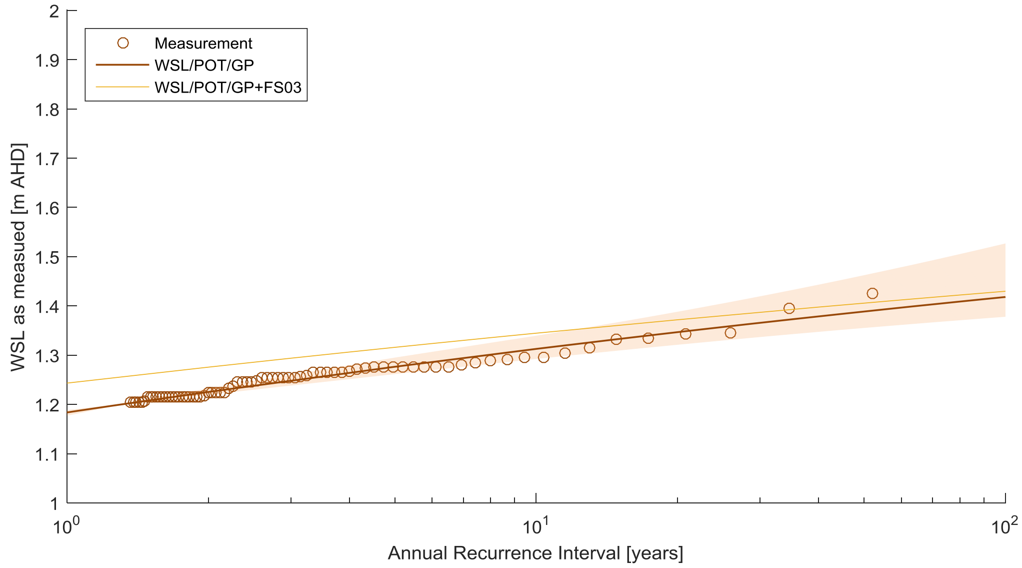

Figure C5.1 Extreme value analysis on WSL without detrending – Fort Denison

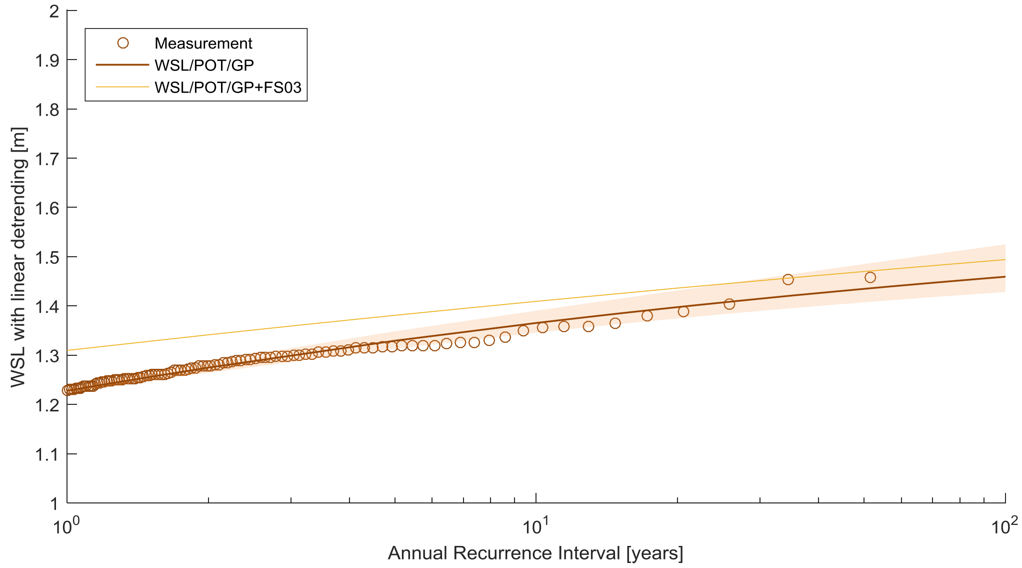

Figure C5.2 Extreme value analysis on WSL with detrending – Fort Denison

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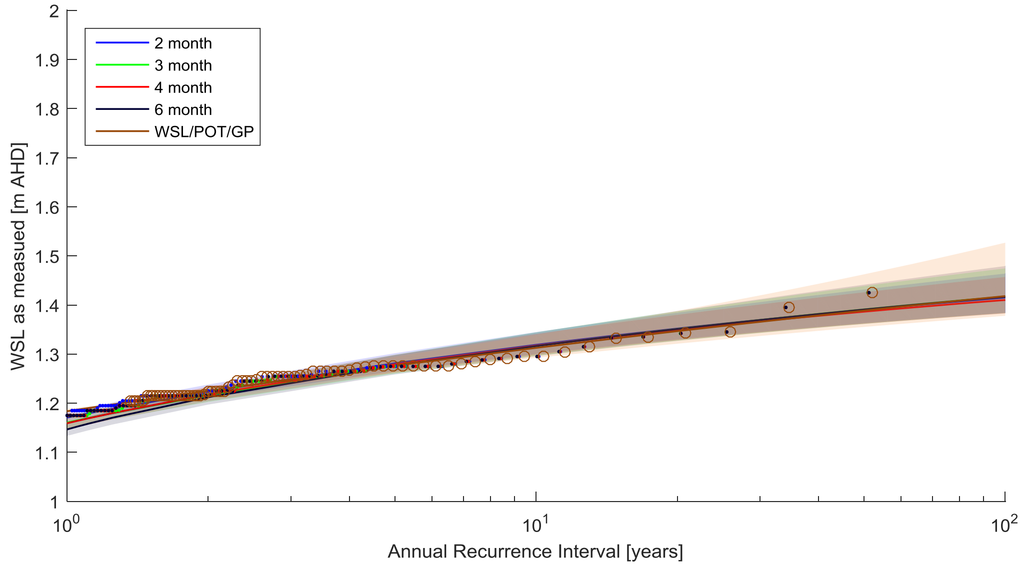

Figure C5.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Fort Denison

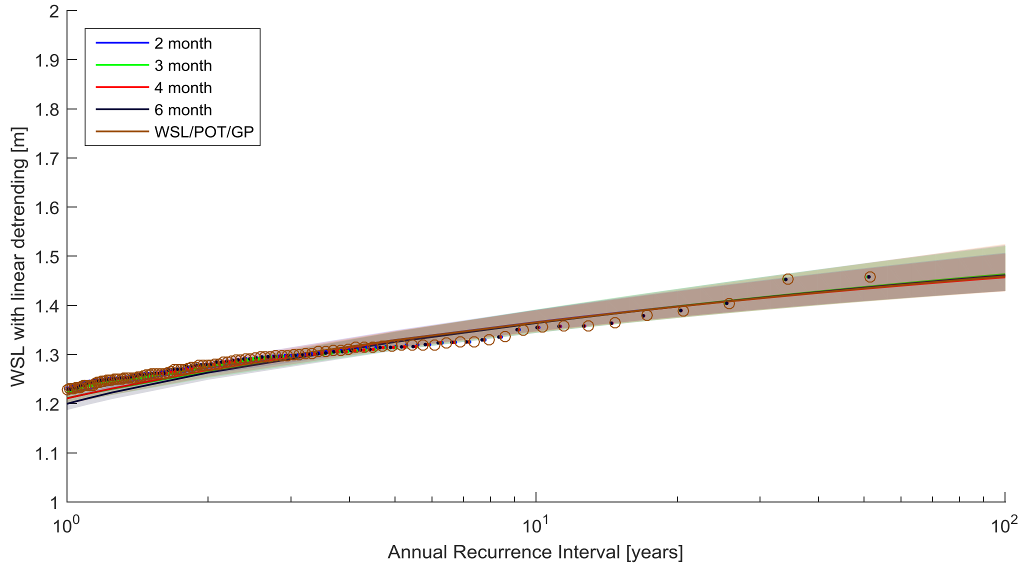

Figure C5.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Fort Denison

Table C6 Sydney Extreme Value Analysis

General information	
Site Name	Sydney
Location	Sydney Harbour, HMAS Penguin
Period of Data	1987-Present
Period of Analysis	24/09/1987-30/06/2016
AWRC	213470
MGA Zone	56
Easting	338841.61
Northing	6255832
Datum	Zero Fort Denison
Adjustment to AHD (m)	-0.925
Classification	Onshore Bay or Port
Logger	CR800
Primary Sensor	Radar
Secondary Sensor	Vented Pressure

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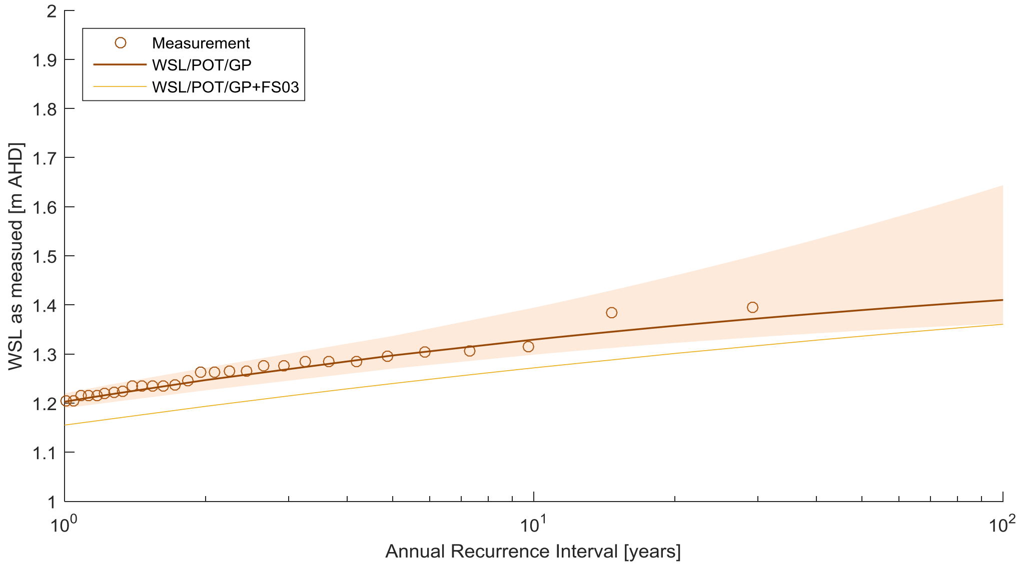

Figure C6.1 Extreme value analysis on WSL without detrending – Sydney

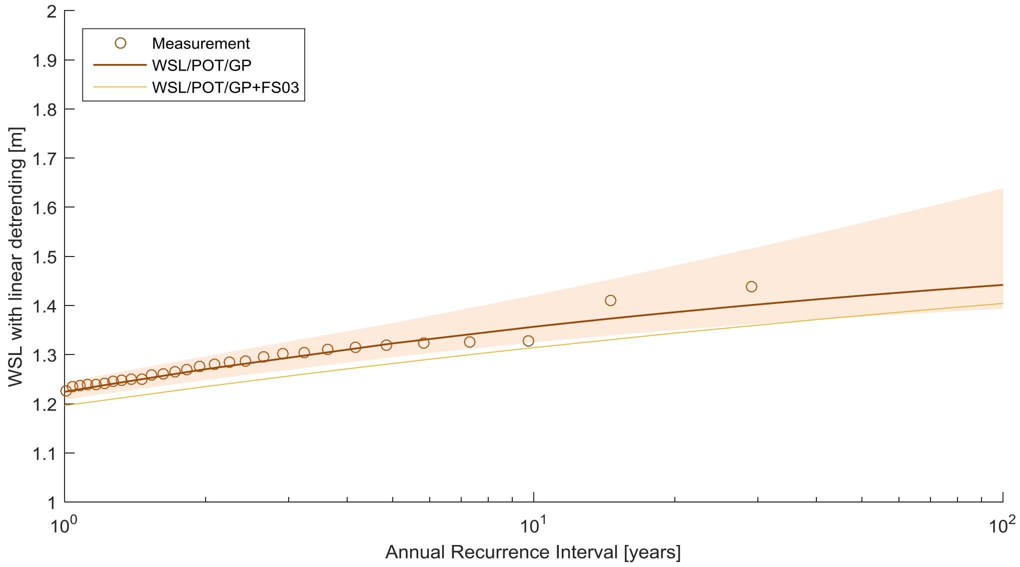

Figure C6.2 Extreme value analysis on WSL with detrending – Sydney

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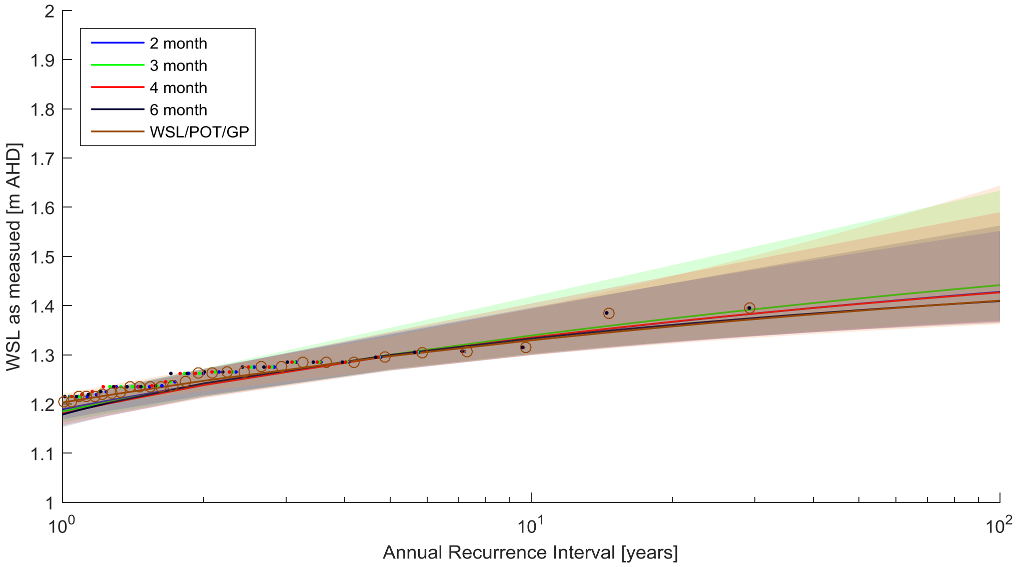

Figure C6.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Sydney

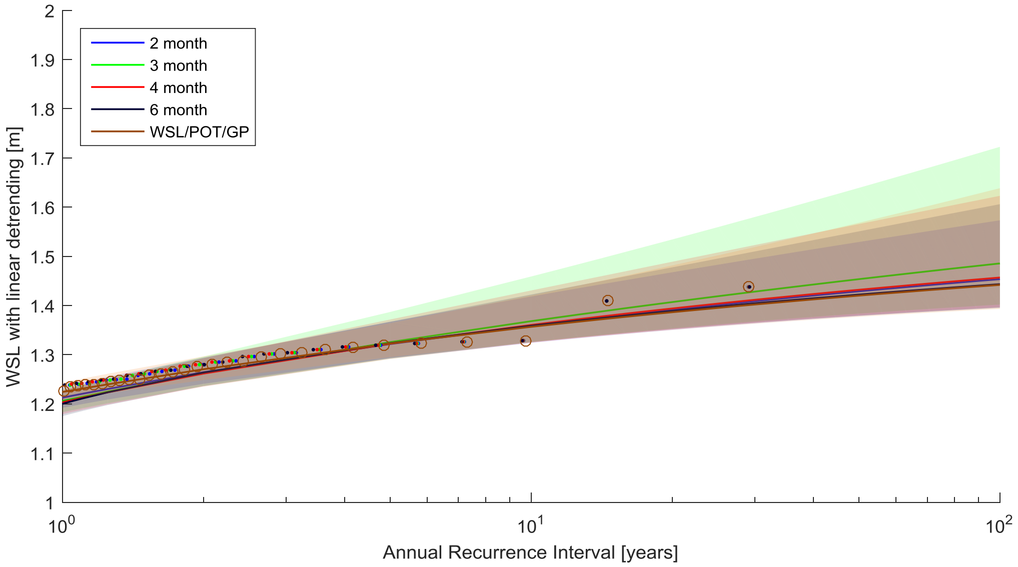

Figure C6.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Sydney

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Table C7 Jervis Bay extreme value analysis

General information	
Site Name	Jervis Bay
Location	HMAS Creswell, Jervis Bay
Period of Data	1989-Present
Period of Analysis	4/9/1989-30/06/2016
AWRC	216470
MGA Zone	56
Easting	291092
Northing	6111027
Datum	Chart Datum (JBPD)
Adjustment to AHD (m)	-1.070
Classification	Onshore Bay or Port
Logger	CR800
Primary Sensor	Radar
Secondary Sensor	Vented Pressure

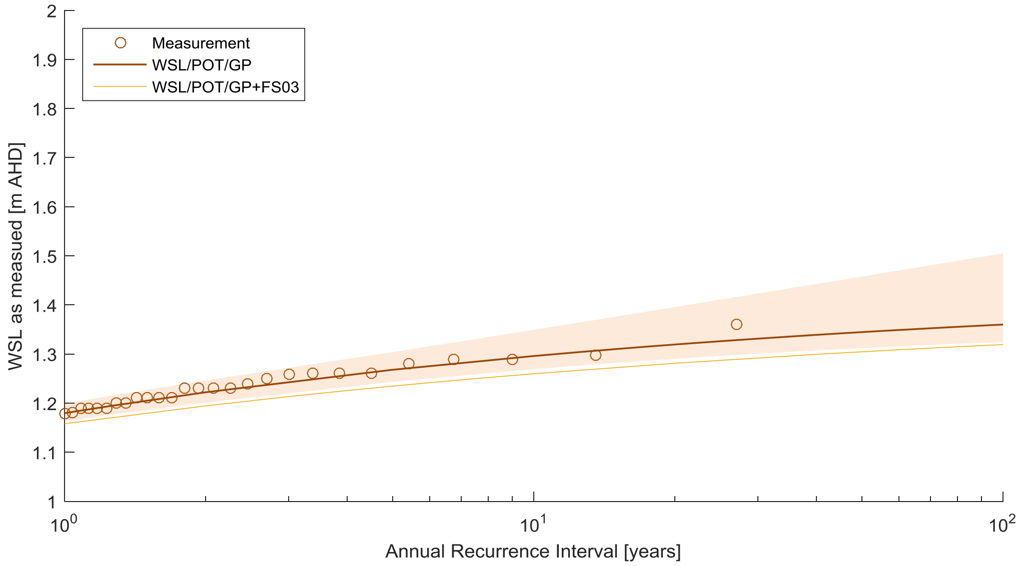

Figure C7.1 Extreme value analysis on WSL without detrending – Jervis Bay

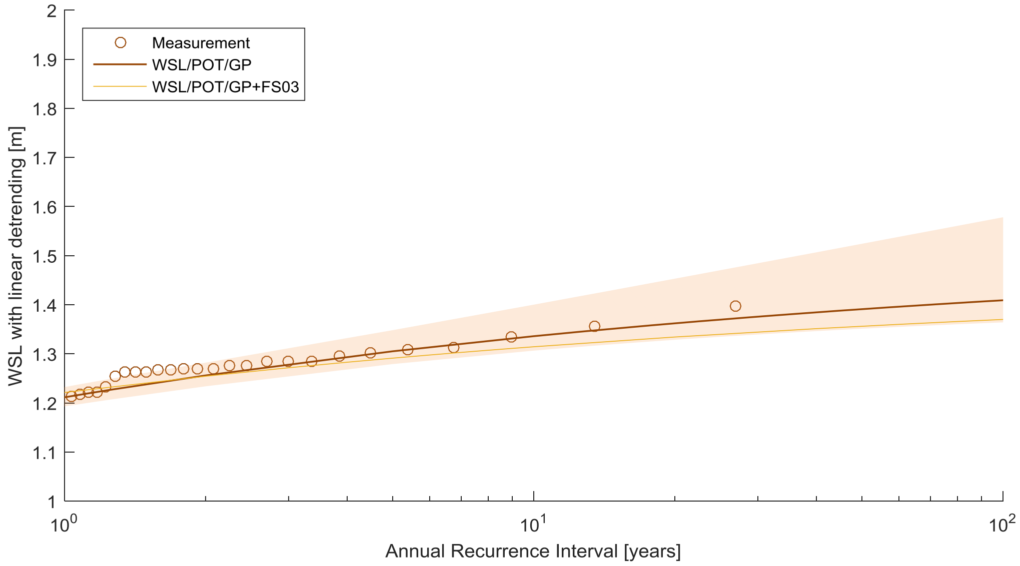

Figure C7.2 Extreme value analysis on WSL with detrending – Jervis Bay

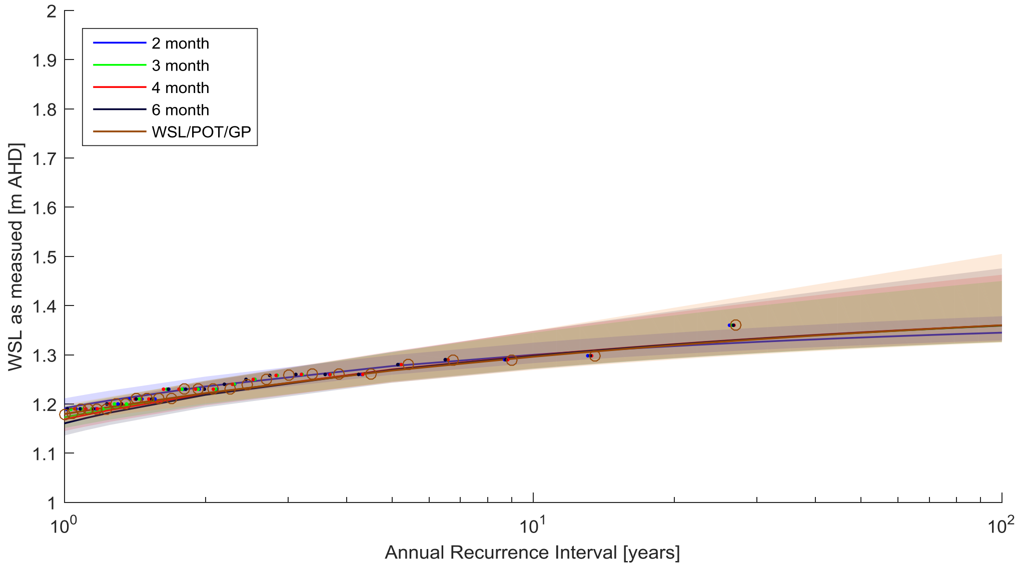

Figure C7.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Jervis Bay

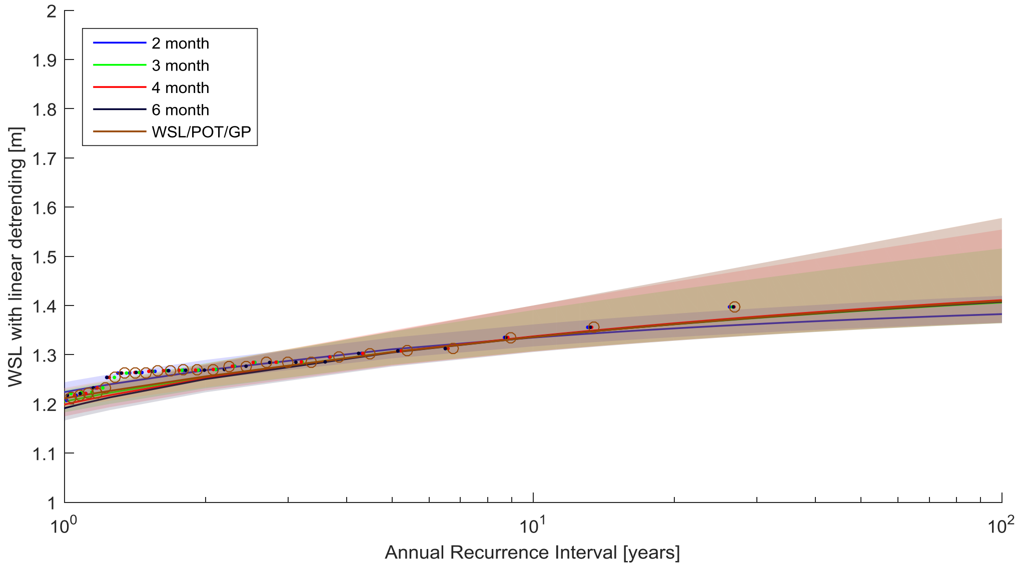

Figure C7.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Jervis Bay

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Table C8 Ulladulla extreme value analysis

General information	
Site Name	Ulladulla Harbour
Location	Ulladulla Harbour
Period of Data	2007-Present
Period of Analysis	24/01/2008-30/06/2016
AWRC	216471
MGA Zone	56
Easting	270711
Northing	6084368
Datum	Australian Height Datum
Adjustment to AHD (m)	0.0
Classification	Onshore Bay or Port
Logger	CR800
Primary Sensor	Vented Pressure
Secondary Sensor	Vented Pressure

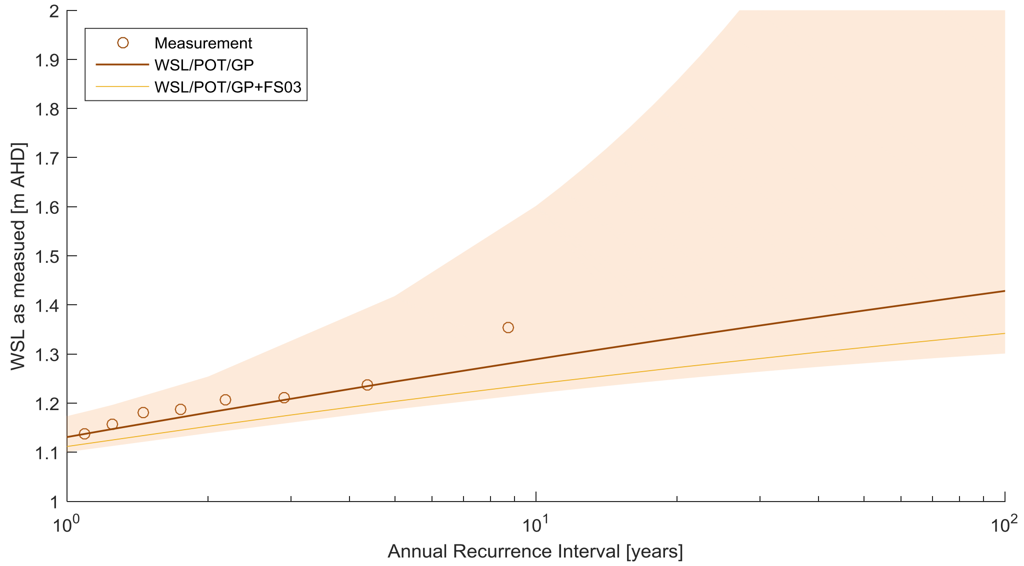

Figure C8.1 Extreme value analysis on WSL without detrending – Ulladulla

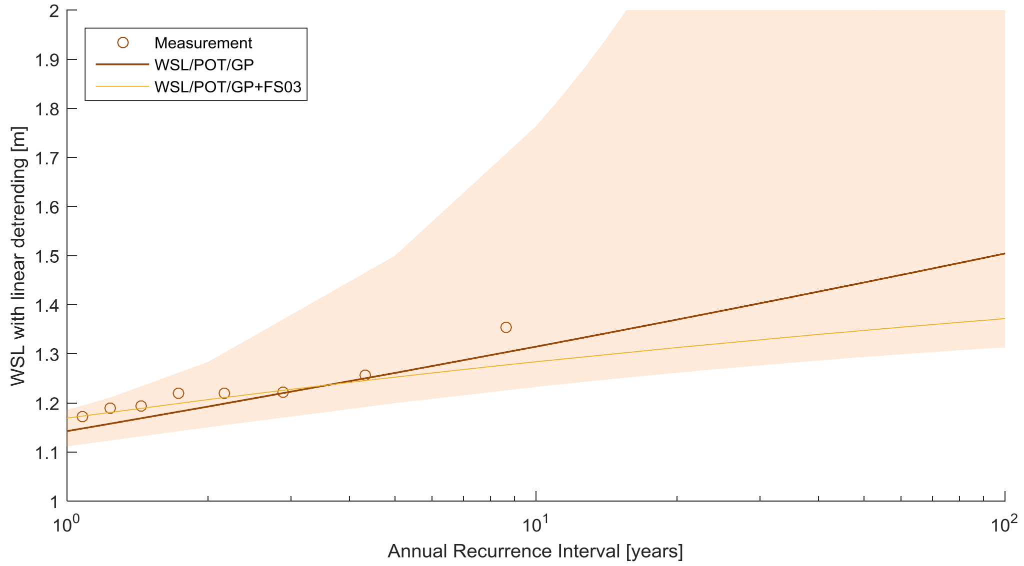

Figure C8.2 Extreme value analysis on WSL with detrending – Ulladulla

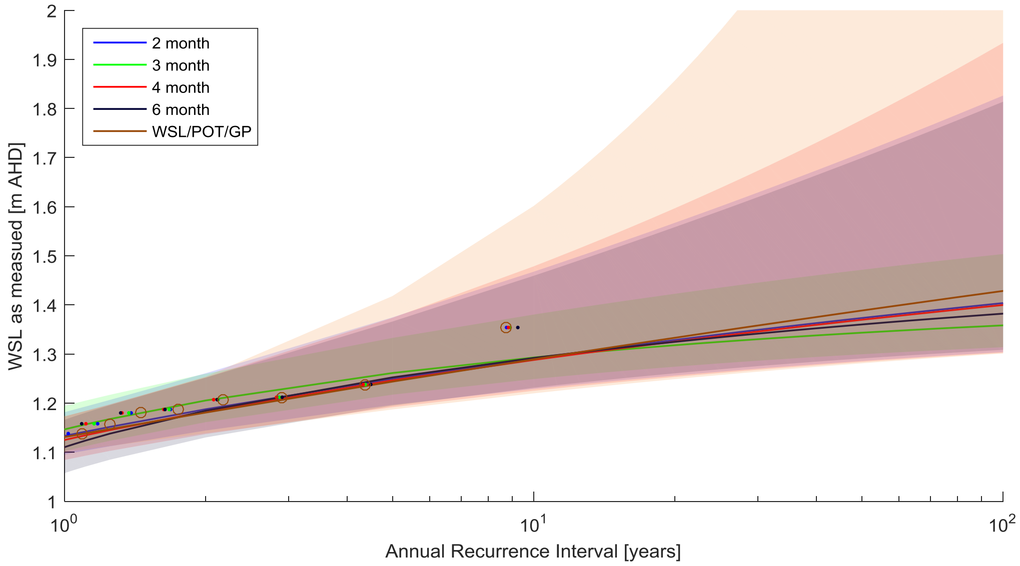

Figure C8.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Ulladulla

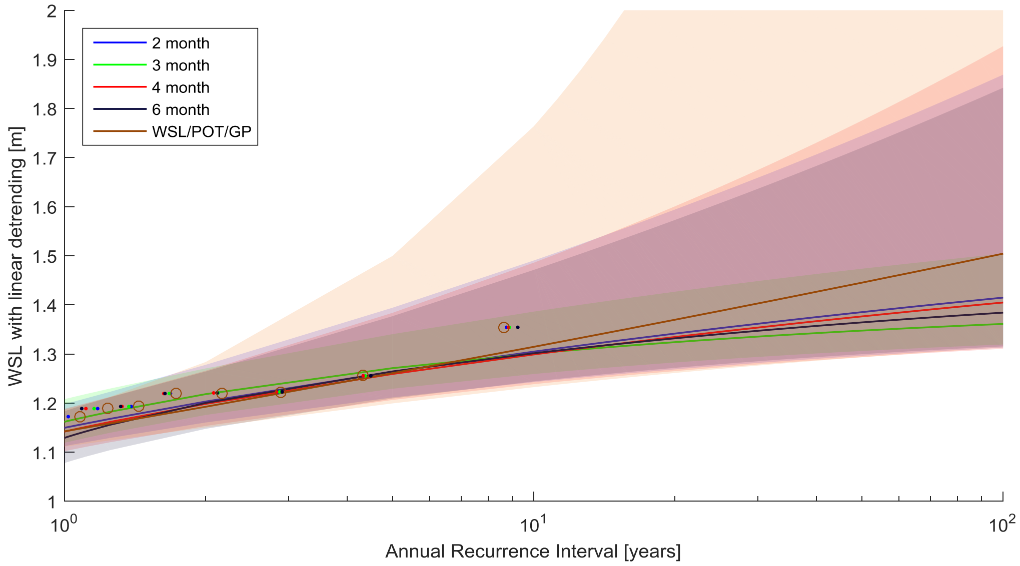

Figure C8.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Ulladulla

Table C9 Eden extreme value analysis

General information	
Site Name	Eden
Location	Eden Boat Harbour
Period of Data	1986-Present
Period of Analysis	19/09/1986-30/06/2016
AWRC	220470
MGA Zone	55
Easting	758557
Northing	5893267
Datum	Twofold Bay Hydro Datum
Adjustment to AHD (m)	-0.924
Classification	Onshore Bay or Port
Logger	CR800
Primary Sensor	Radar
Secondary Sensor	Vented Pressure

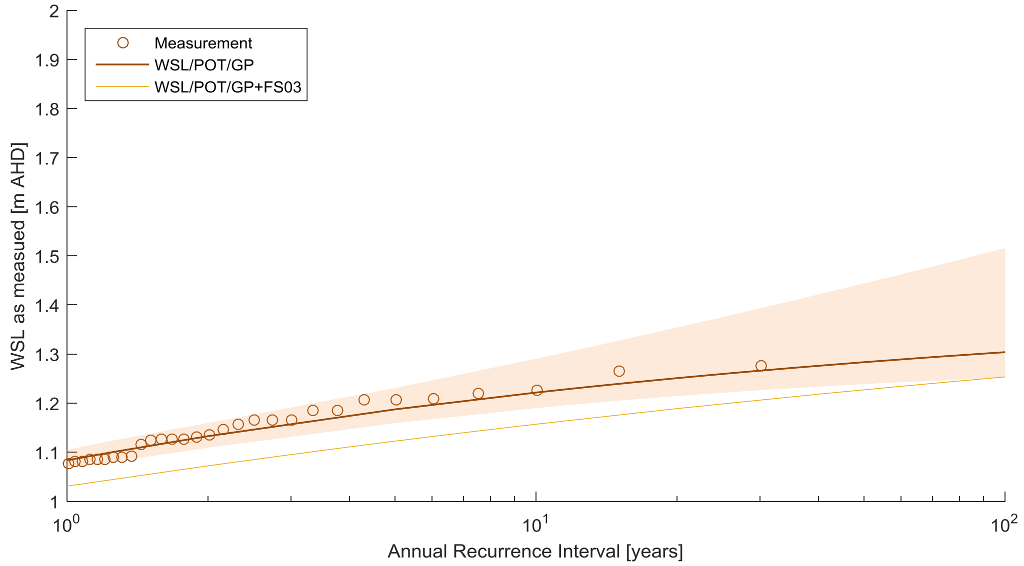

Figure C9.1 Extreme value analysis on WSL without detrending – Eden

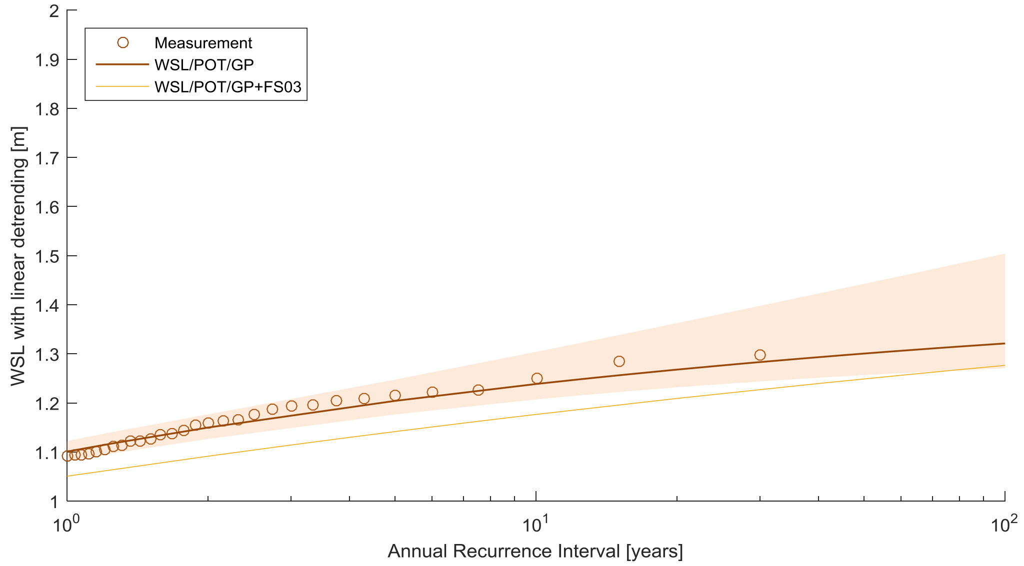

Figure C9.2 Extreme value analysis on WSL without detrending – Eden

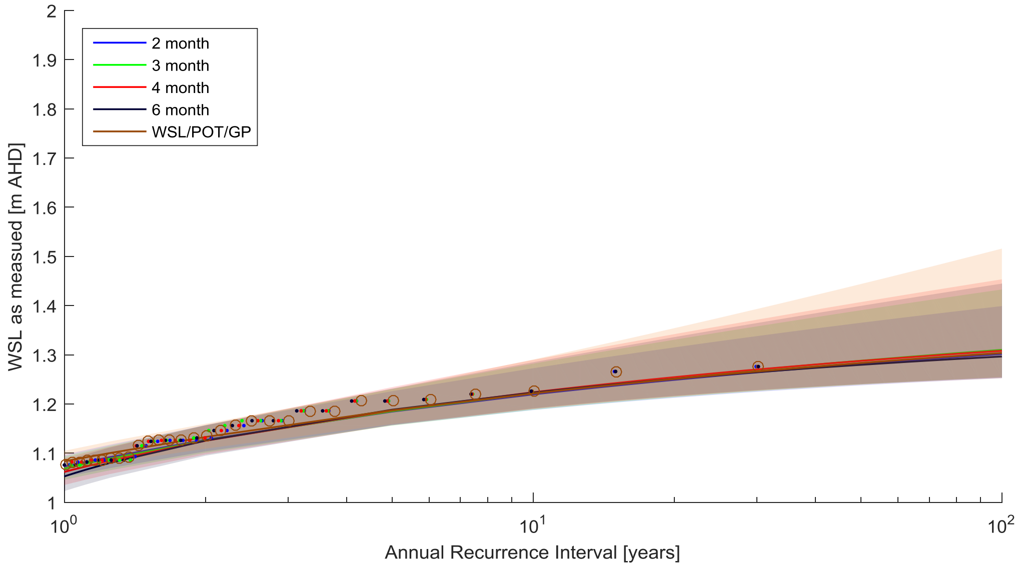

Figure C9.3 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL without detrending – Eden

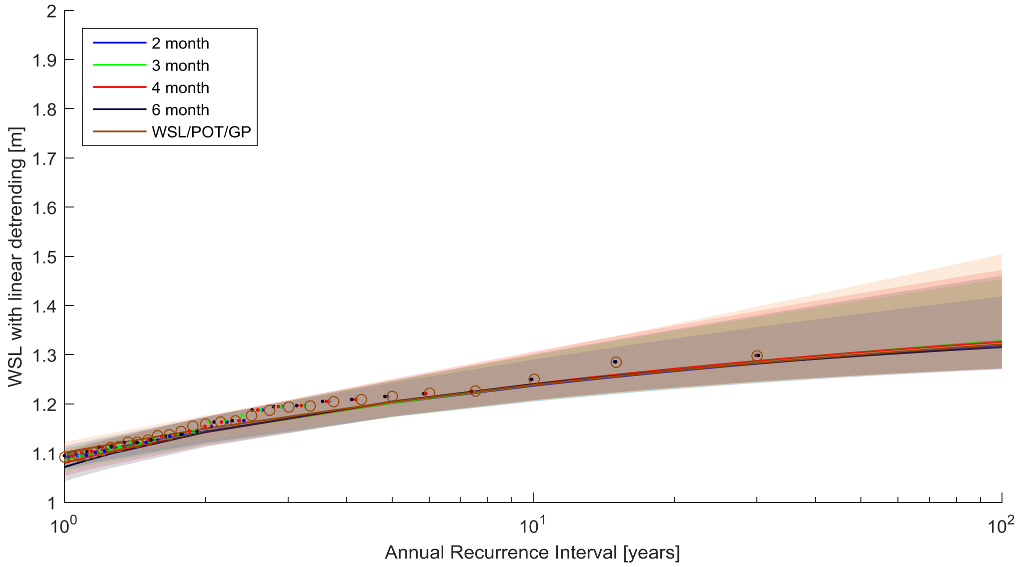

Figure C9.4 Comparison of peaks over threshold and block maxima in extreme value analysis on WSL with detrending – Eden

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Appendix D. Fort Denison extreme value analysis

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AUSTRALIA

Water Research Laboratory

29 November 2016

WRL Ref: WRL2016087 LR20161129

COMMERCIAL IN CONFIDENCE

Mr Edward Couriel
Director
Manly Hydraulics Laboratory
Department of Finance, Services and Innovation
110B King Street
Manly Vale NSW 2093

Edward.Couriel@mhl.nsw.gov.au

Dear Ed,

Fort Denison Extreme Value Analysis

1. Introduction

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Australia is pleased to provide this report to Manly Hydraulics Laboratory (MHL) Department of Finance, Services and Innovation, summarising the findings of an investigation of climate effects on tidal extremes in NSW. This work will contribute to a broader study of ocean water levels in NSW, undertaken for the NSW Office of Environment and Heritage (OEH).

Extreme water levels are a critical consideration for any coastal or estuarine application, yet the derivation of the recurrence interval of extremes is complicated by the many processes that contribute to sea levels. Relatively simple univariate approaches have been shown to provide good estimates, but the importance of the result to coastal management means that the uncertainty in the analysis should be well understood.

Recent work (MHL1881, MHL2366) demonstrates that many factors can contribute to uncertainty in the analysis of tide gauge data, particularly for extreme events at high ARI intervals. One aspect is the uncertainty associated with climate variability.

Climate cycles can affect sea levels through a range of mechanisms, both oceanographic and meteorological. These may influence water level statistics from mean sea level to sea level extremes. An important implication of this is that the available measured data may not be representative of a future period. For NSW, where many of the gauges have a 25-30 year record, longer climate cycles with durations in the order of, or longer than, the current record may provide additional uncertainty that needs to be factored in to forecast levels.

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2. Methodology

The magnitude of the impact of climate cycles on water level was determined by performing extreme value analysis on multiple periods of Fort Denison data. The periods of analysis included overlapping blocks of 18.61years. This period, equal to a full lunar nodal cycle, was chosen to minimise the impact of the long period astronomical forcing on the analysis. The results from the extreme value analysis of each period were compared to determine the magnitude of variability. This indicates the variance in extremes that is experienced over time.

Water level data for Fort Denison was supplied by MHL and included significant additional quality coding on the data originally supplied by the National Tidal Centre. The dataset used in this study is illustrated in Figure 1.

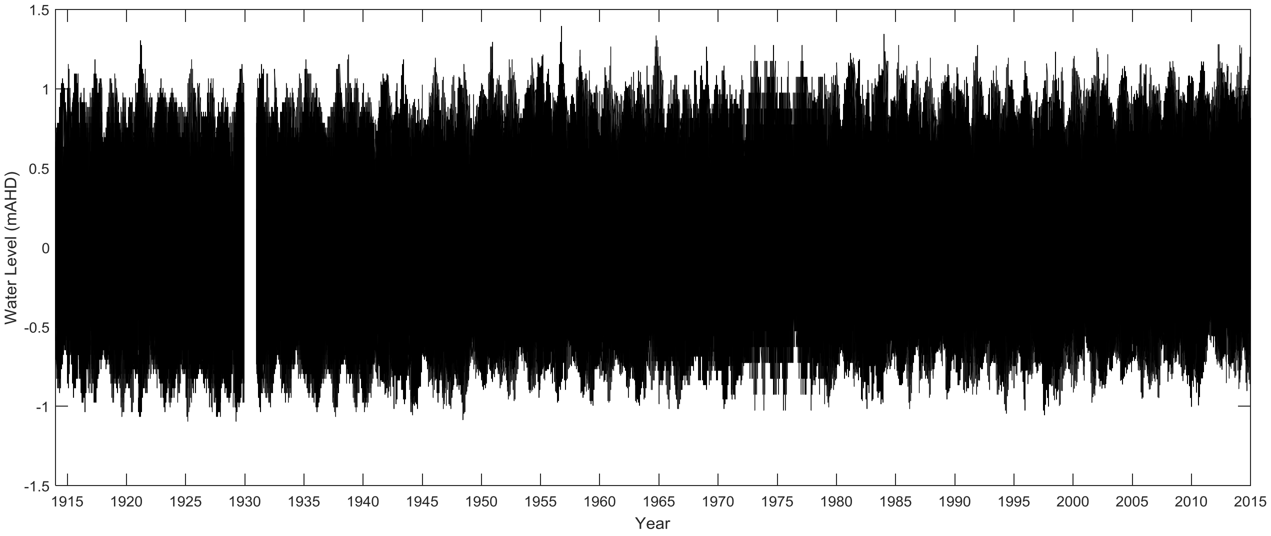

Figure 1: Measured Fort Denison water level data after quality coding

Detrending

Sea level rise is a complicating factor. Previous analysis (MHL1881) has shown the rate of sea level rise is not linear over the record, with strong evidence for accelerating rates. Sea level rise analysis is also influenced by longer climate cycles such as the Interdecadal Pacific Oscillation (IPO) which operates over periods of 20-60 years, and there may be other long cycles involved.

Long historical datasets tend to underestimate extreme water levels because the early part of the record is lower than the current levels due to sea level rise. The early extremes are lower than they would be when compared to present day water levels.

Similarly, a linear detrending of the data can artificially accentuate events in parts of the record. Fort Denison is a case in point, where levels remained relatively constant up to the 1940's and 1950's. Around that time there was a rapid rate of change in water levels before returning to a more moderate rate of rise. For a linearly detrended dataset, this results in very high extremes through the middle portion of the data record.

An alternative detrending technique uses a rolling average to bring the mean sea level to match the level at a reference date. This study adopted a 30-year rolling average, and adjusted the levels so that the 30-year average around each point was the same as the average of the period 1985-2015. This was chosen to remove signals associated with very long climate variability and sea level rise, but still maintain the influence of shorter climate cycles, specifically the southern oscillation index (SOI). See Figure 2.

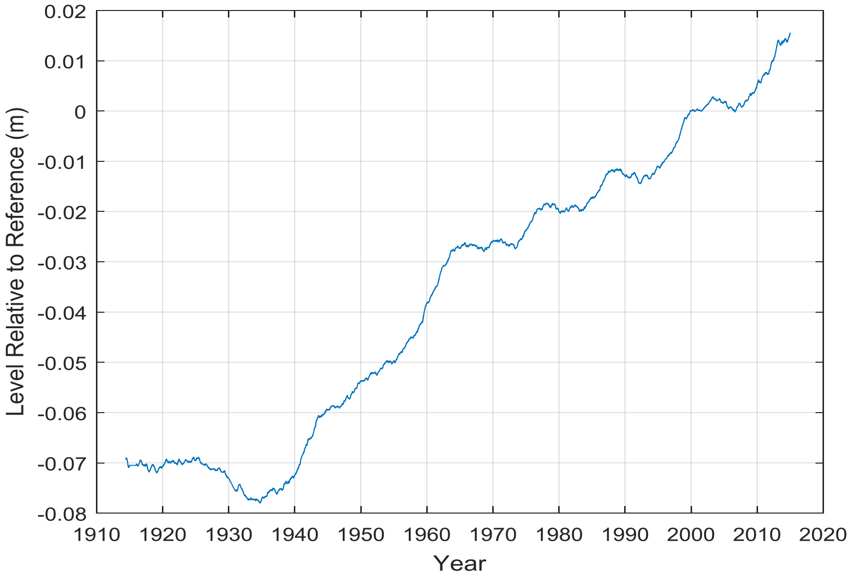

Figure 2: 30-year mean water levels relative to the period 1985-2015

To consider the impact of detrending, the analysis was performed in two parts. The first using the measured data, the second using a detrended data set.

Declustering

Extreme value analysis requires that the data points selected for analysis are independent. However, in a typical tide record, the time interval between each recorded value is often short, and therefore extreme water level events may be sampled over numerous consecutive samples in the record. The process of selecting the highest data point in each event is known as declustering.

The declustering in this study used a threshold near the mean high water level, and a run length of six (6) days. This generally resulted in the highest point of each spring cycle being selected for the set of extremes.

Generalised Pareto Distribution (GPD)

The Generalised Pareto Distribution (GPD) approach to extreme value analysis is a technique commonly applied to water level extremes. It has an advantage over the generalised extreme value (GEV) block maxima approach by using all extremes in the dataset. This study uses the method described in Coles (2001) and was performed using the extRemes package adapted from Coles original code (Gilleland et al., 2016)) in R (R Development Core Team, 2008).

The GPD is a peaks-over-threshold model, which fits the model to all points over a chosen threshold. The points are selected from the declustered dataset to ensure independence of the data, and the number of events may vary from year to year (unlike a block maxima). Threshold selection is a key part of the modelling process, and particularly impacts the shape of the confidence intervals. The threshold must be chosen to allow fitting to greatest number of extreme events, without being unduly affected by the central mode, and there are a number of goodness-of-fit tests employed to validate the fit.

GPD fits were performed on each period of data, across both measured and detrended datasets.

3. Results

The results of the GPD fitting are provided in Figure 3 for the measured dataset, and in Figure 4 for the detrended dataset.

The results show that the analysis is sensitive to the period of record analysed. The analysis of measured data shows a variation in forecast extremes of approximately 0.21 metres.

The analysis of the detrended data showed less variability in forecast extremes than the measured data, and this is consistent with the variability introduced by nearly 0.1 m of sea level rise over the record. The very low extreme value fits all come from the early decades of the data. The detrended data shows a variation in forecast extremes of approximately 0.15 metres.

For future extreme water level projections it is recommended to use the uncertainty derived from the detrended results, together with suitable allowance for sea level rise, including a consideration of uncertainty in the projections.

The GPD is a univariate model, meaning that it assumes that a single process drives the variability in the water levels. This is not the case as water levels are affected by tides, storm surge, winds, ocean currents, coastally trapped waves and other phenomena. While the use of a univariate model is not strictly appropriate for modelling sea levels, multivariate analysis on the many small drivers of tidal anomalies is complex and not commonly applied to sea levels in Australia. While univariate models have been widely adopted, this is a key area for further research.

4. Conclusion

Thank you for the opportunity to provide this advice. Please contact Ben Modra or myself should you require further information.

Yours sincerely,

Grantley Smith
Manager

5. References

Coles, S., (2001) An introduction to statistical modeling of extreme values, London, U.K.: SpringerVerlag, 208 pp.

Gilleland, E.,. Katz, R. E., (2016). extRemes 2.0: An Extreme Value Analysis Package in R. Journal of Statistical Software, 72(8), 1-39. <doi:10.18637/jss.v072.i08>

MHL1881, (2011) *NSW Tidal Anomaly Analysis*, NSW Department of Finance and Services, Manly Hydraulic Laboratory.

MHL2366, (draft) *NSW Ocean Water Levels*, NSW Department of Finance, Services and Innovation, Manly Hydraulic Laboratory.

R Development Core Team, (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

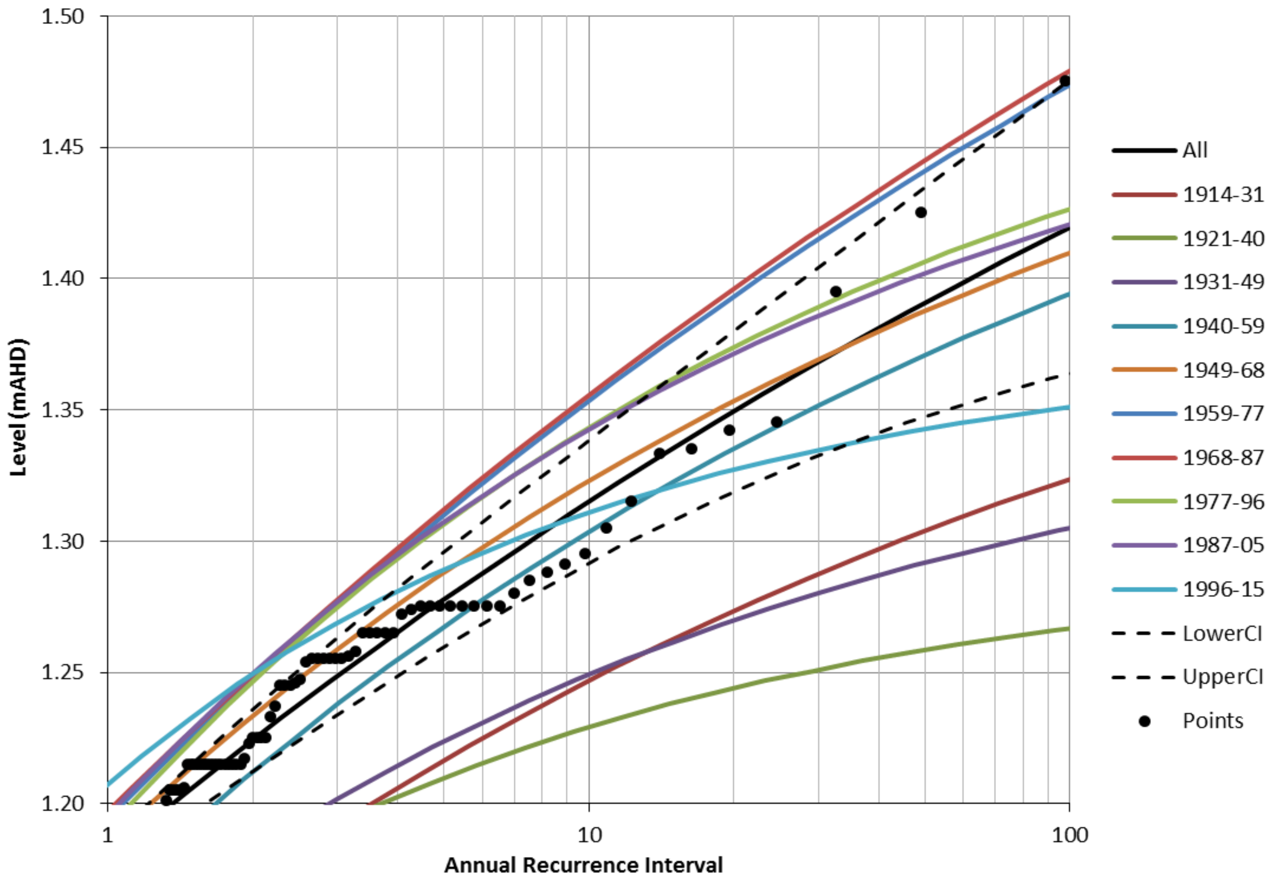

Figure 3: Results of the analysis of measured Fort Denison data

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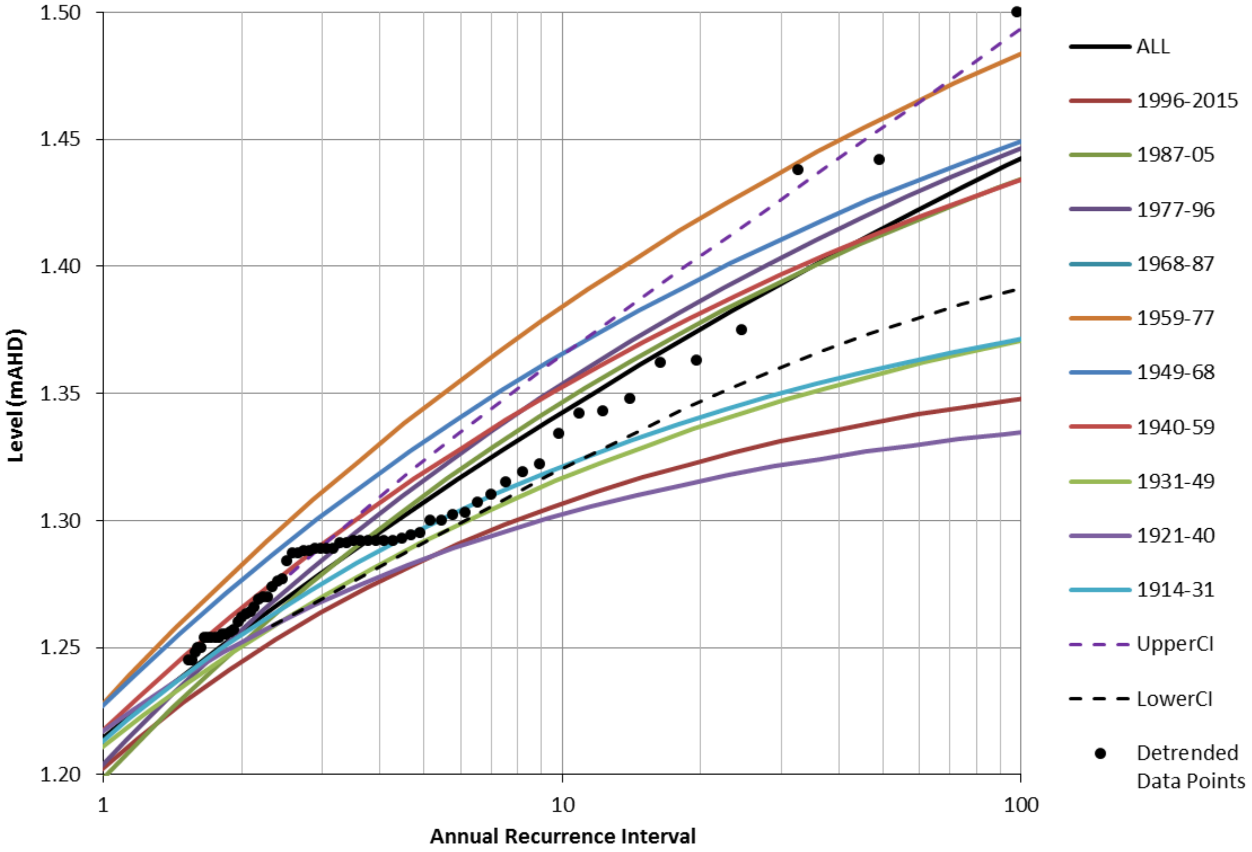

Figure 4: Results of the analysis of detrended Fort Denison data

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Appendix E. Review of extreme value analysis methodology

The following review of the extreme value analysis methodologies adopted in this report was undertaken by Dr David Callaghan of the University of Queensland. The review includes some additional analysis as detailed below to test the uncertainties attributable to different event identification methods and the significance of this on estimating extreme ocean water levels for NSW.

The existing extreme value event identification method (‘**peak-over-threshold**’) selects events that exceed a given elevation threshold of two standard deviations above the mean which are at least 6 days apart. This approach assumes peaks occur randomly in time and follow a Poisson process (Anonymous, 2011, Page 122, Section 6.3.3). When this approach is applied to water surface levels, it is improbable that these two assumptions hold. For example, this method will select events that are collocated with spring tides.

An alternative approach is to assign the main mechanism responsible for each tidal anomaly and hence, separate them based on event type. This approach requirements significant manual work well beyond the scope of the present study and separating tidal anomalies into their generation mechanism is also problematic (for example, there may be concurrent drivers such as a shelf wave with an east coast low).

Another alternative approach is to estimate tidal anomaly, model its events and then recombine with the astronomical deterministic tide. The maximum operator gradient approach (‘**max-gradient-approach**’) selects events when the maximum tidal anomaly function (blue line of Figure E1), obtained by finding the maximum in a moving window of δ on tidal anomalies (orange line of Figure E1), is constant for a considerable amount of that window size ($a \times \delta$ and $0 < a < 1$). This approach is implemented by determining when

$$\frac{\partial}{\partial t} \max \left\{ \eta \left(t \in \left[t - \tfrac{\delta}{2} ; t + \tfrac{\delta}{2} \right] \right) \right\}$$

is continuously zero for a duration of at least $a \times \delta$ (Callaghan, 2008).

The 1974 events at Fort Denison (Figure E1) selected by ‘**peak-over-threshold**’ and ‘**max-gradient-approach**’ are somewhat different. The ‘**peak-over-threshold**’ has selected three events between 22 May and 15 June, compared with two from ‘**max-gradient-approach**’. Foster et al. (1975) shows that between these two dates, two meteorological events occurred. The false positive from the ‘**peak-over-threshold**’ method is an example of spring tide bias.

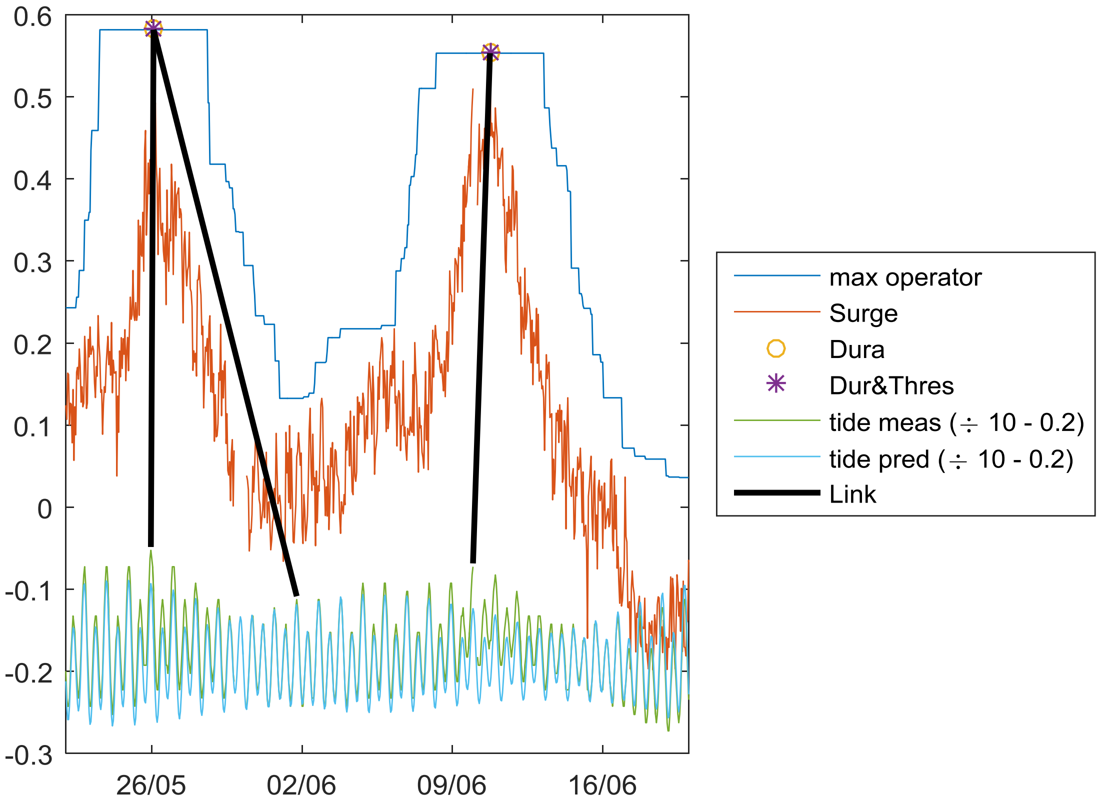

Figure E7.1—Fort Denison water surface levels (green line for measured and light blue for predicted, both divided by 10 and offset by -0.2 m), maximum operator using δ = 5 days (dark blue line) with event selected when its gradient is zero for 0.7×5 days (a = 0.7, red star and orange circle). The selected events from the maximum operator gradient approach are linked to the nearest selected events from the existing event selection (peak-over-threshold) approach.

Comparing '**peak-over-threshold**' and '**max-gradient-approach**', it is concluded that the

- '**peak-over-threshold**' is effective at event identification, albeit with some bias towards Spring Tide events; and
- large surges are occurring during Neap Tides and below high tide which are being missed by the adopted '**peak-over-threshold**' method.

The separation approach used to estimate tide anomaly (Figure E1, surge) has many well-known issues and generally is a noisy signal. The question then becomes, "*does this noise impact extreme value determination?"*

As for the '**peak-over-threshold**' method, the Generalised Pareto distribution was used to model tidal anomalies, which were recombined with tide using empirical event durations (broken into 10 bins containing equal numbers of events). Using Fort Denison data (Figure E2), the '**peak-over-threshold**' method has systematically higher estimates than the '**max-gradient-approach**'. A proportion of these differences in estimates are from the Generalised Pareto fit to the tail being below the last four measured tidal anomalies (Figure E2). A proportion will be from the bias of the '**peak-over-threshold**' method selecting more events during spring tides. In either case, the magnitude of both combined is circa 0.1 m.

Applying both the ‘**peak-over-threshold**’ and the ‘**max-gradient-approach**’ to Coffs Harbour, Crowdy Head, Port Stephens, Patonga, Sydney, Jervis Bay, Ulladulla and Eden gauge data confirms this difference (see Figure E3 to E10).

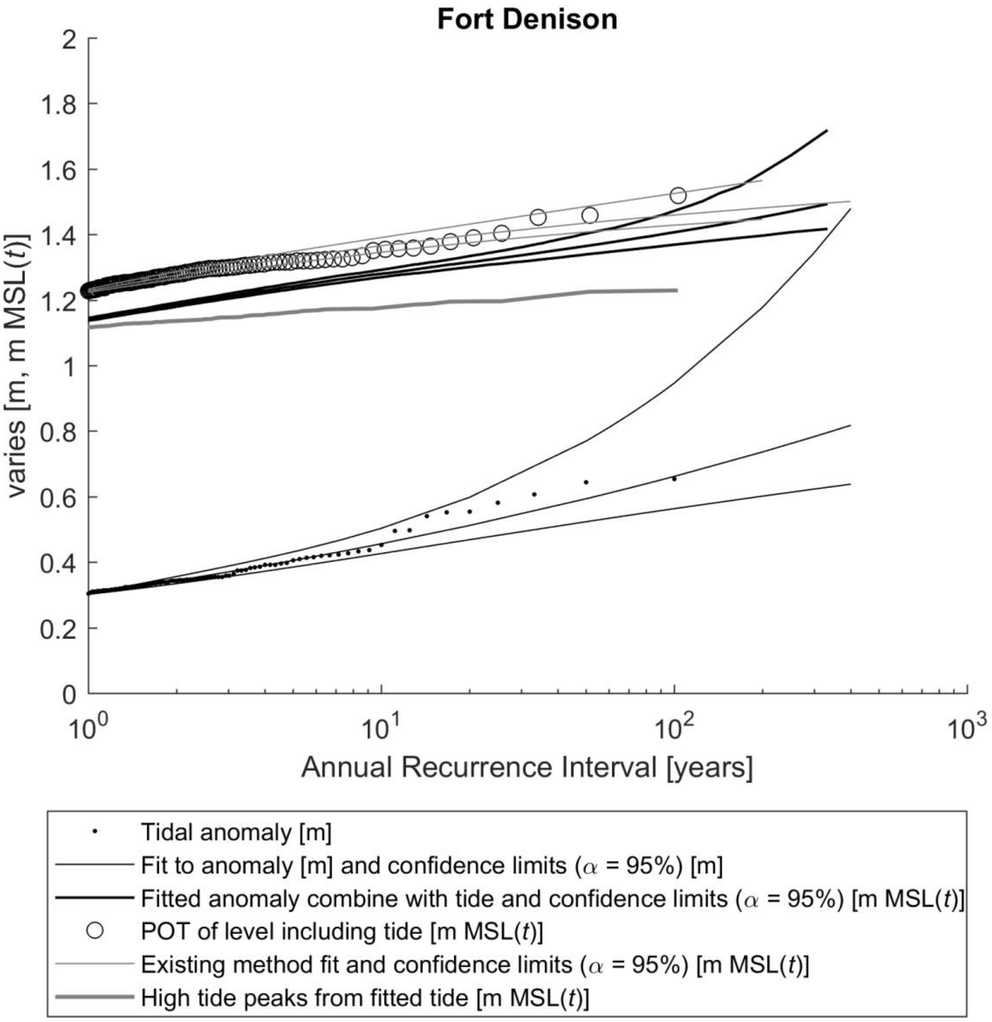

Figure E7.2—Full parametric analysis at Fort Denison. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, ‘peak-over-threshold’ (data, expectation and confidence limits) and tidal ‘extremes’ are included.

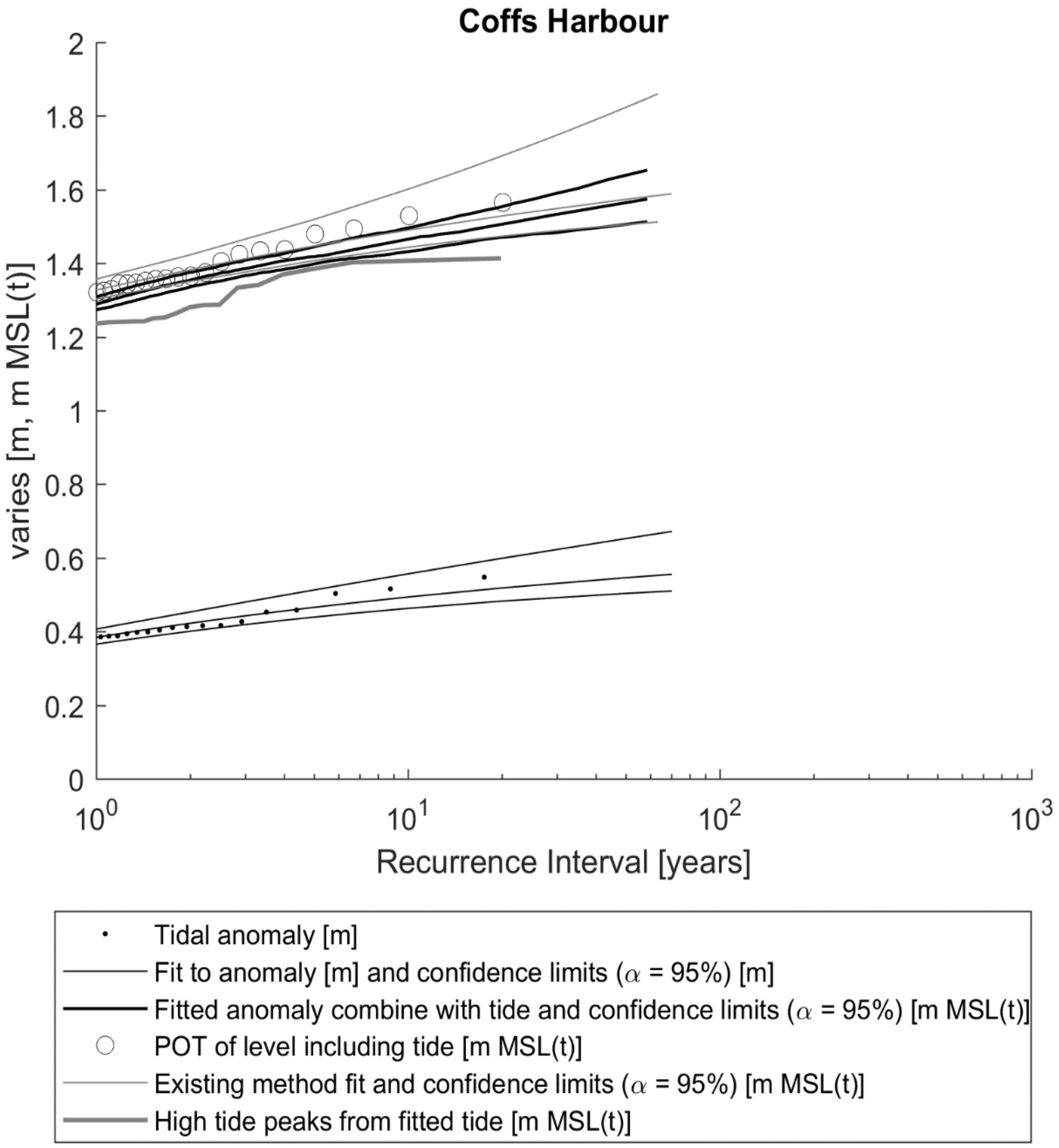

Figure E7.3—Full parametric analysis at Coffs Harbour. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, 'peak-over-threshold' (data, expectation and confidence limits) and tidal 'extremes' are included.

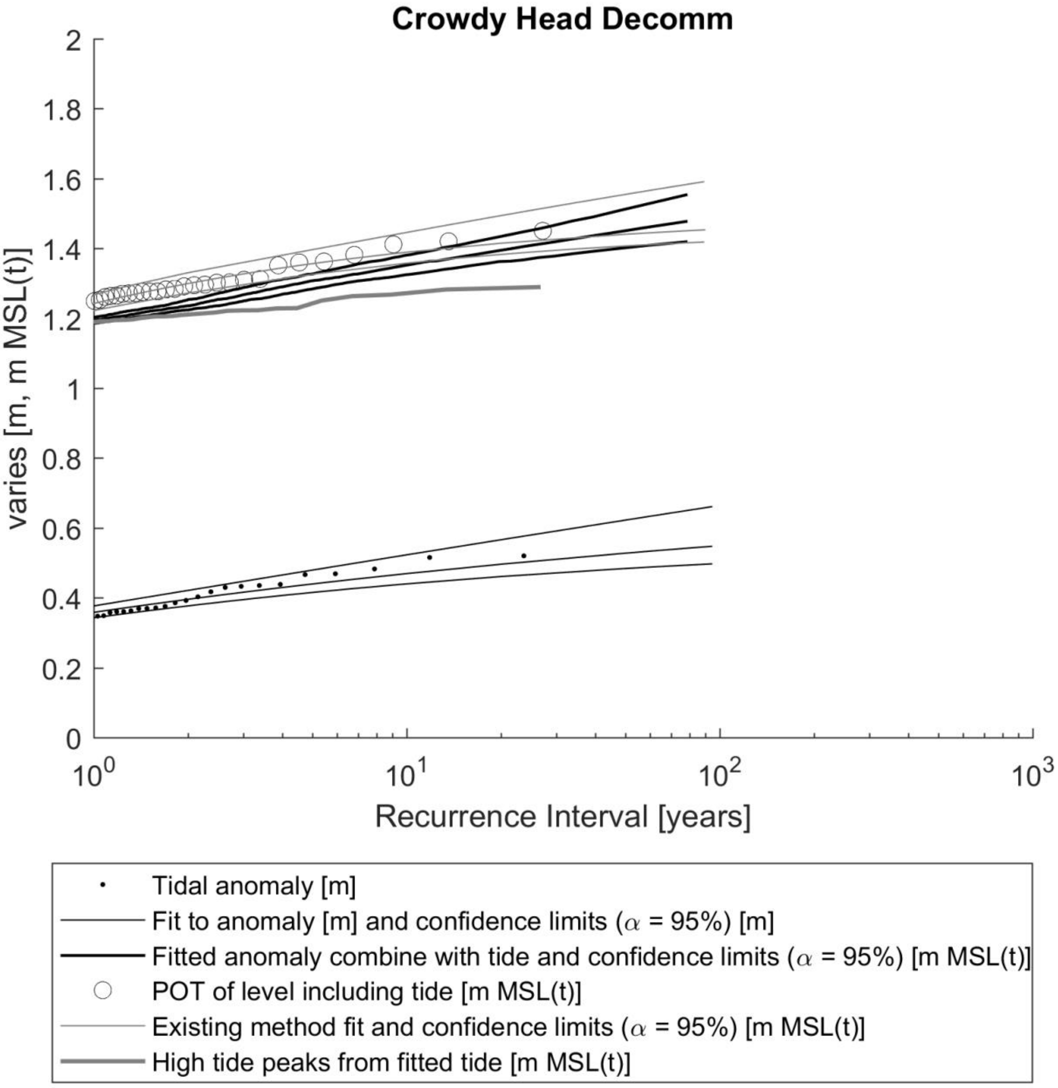

Figure E7.4—Full parametric analysis at Crowdy Head. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, 'peak-over-threshold' (data, expectation and confidence limits) and tidal 'extremes' are included.

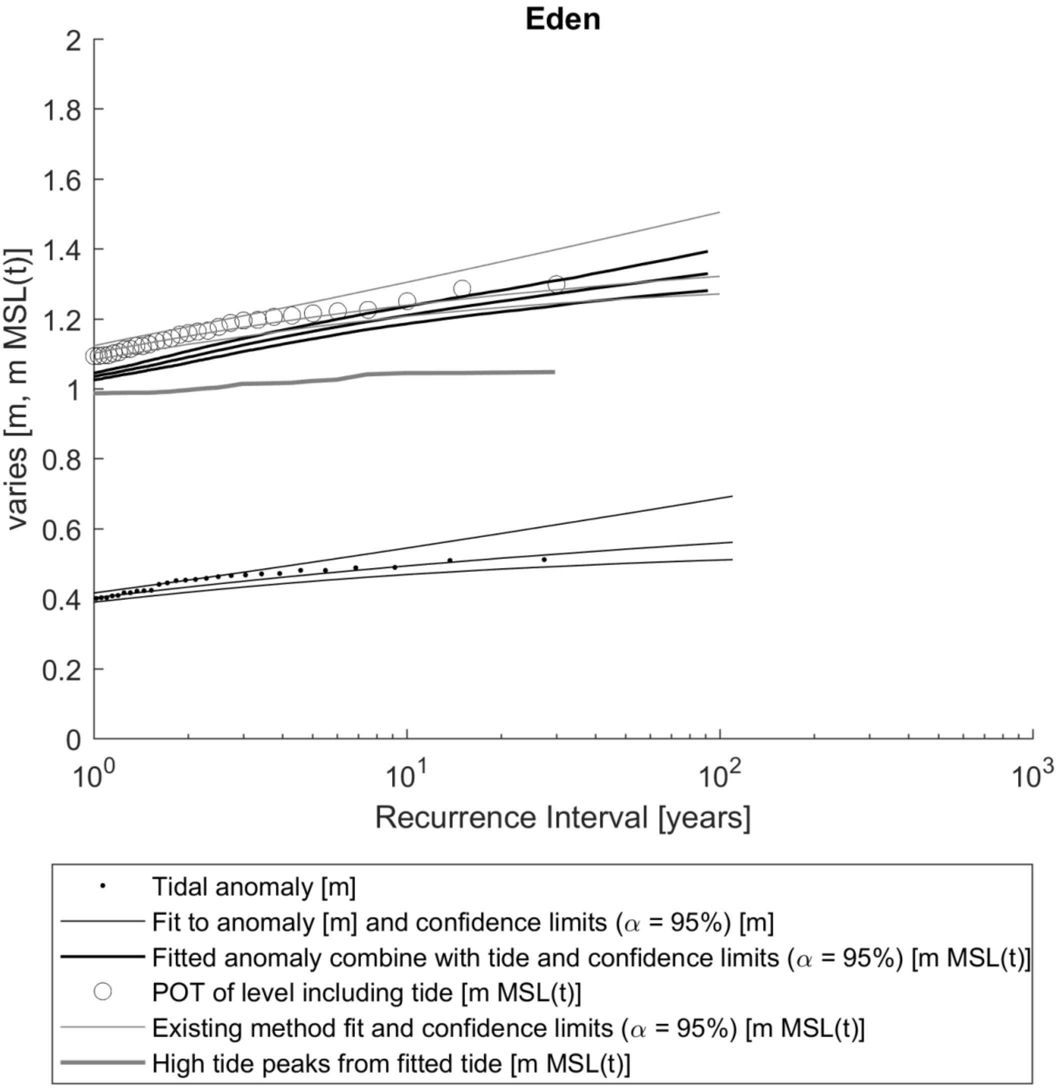

Figure E7.5—Full parametric analysis at Eden. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, ‘peak-over-threshold’ (data, expectation and confidence limits) and tidal ‘extremes’ are included.

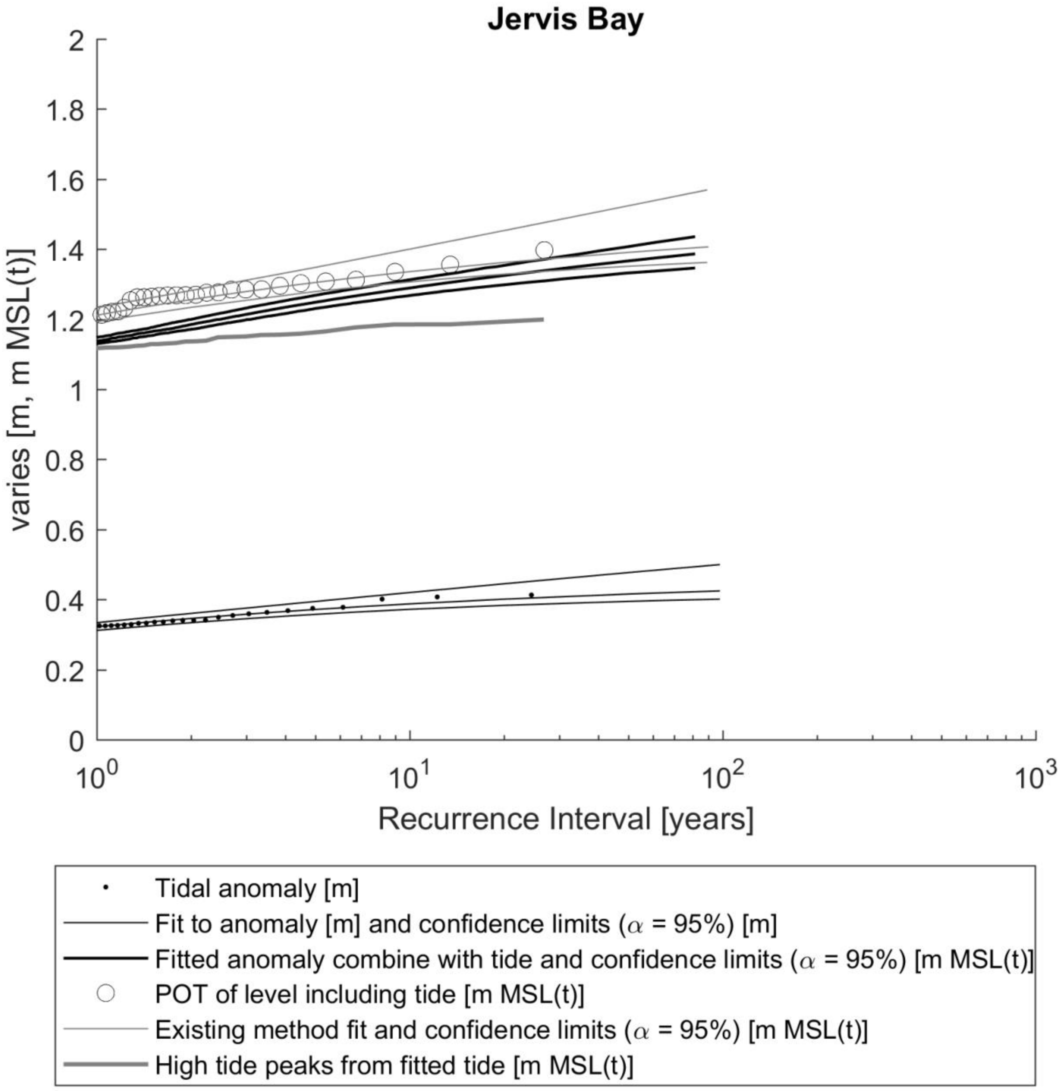

Figure E7.6—Full parametric analysis at Jervis Bay. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, 'peak-over-threshold' (data, expectation and confidence limits) and tidal 'extremes' are included.

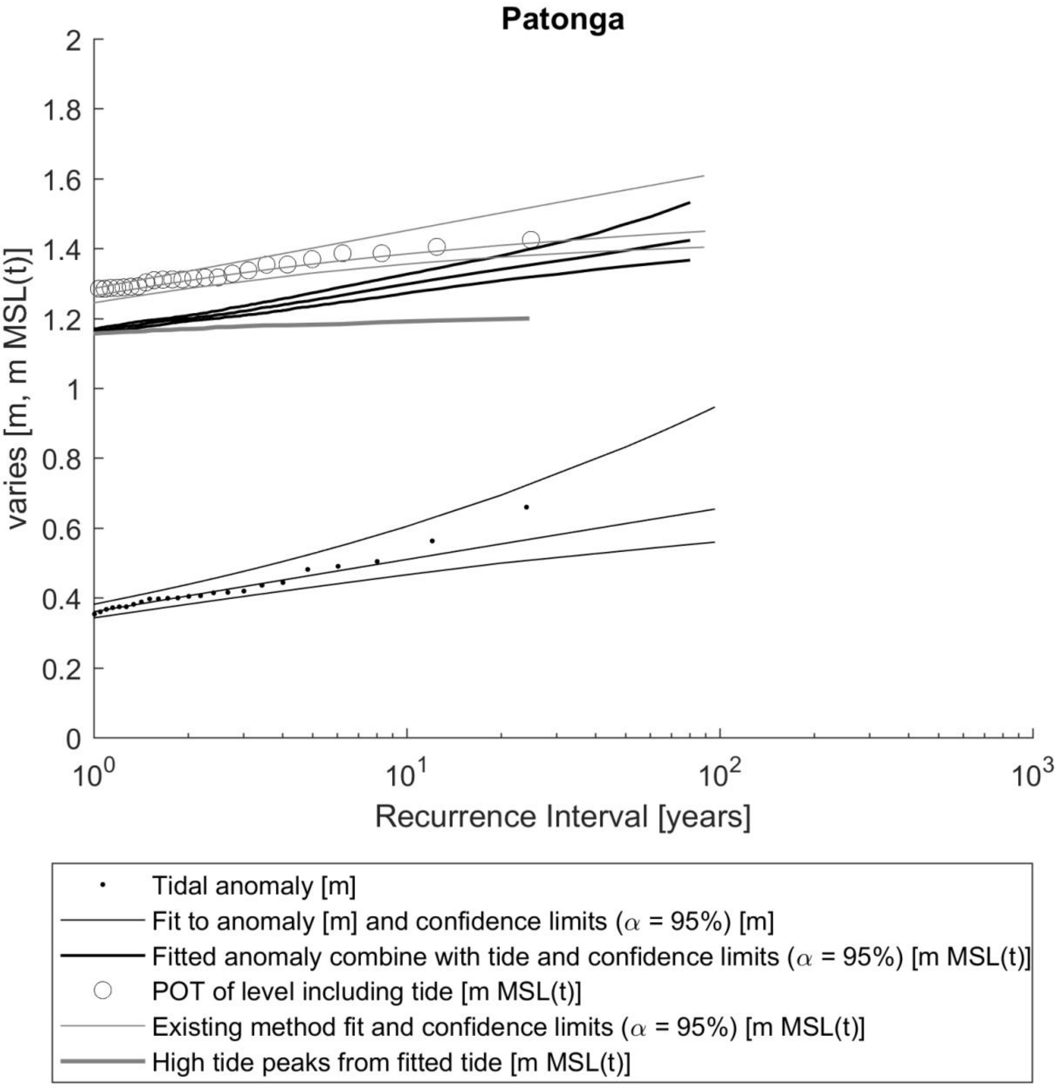

Figure E7.7—Full parametric analysis at Patonga. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, 'peak-over-threshold' (data, expectation and confidence limits) and tidal 'extremes' are included.

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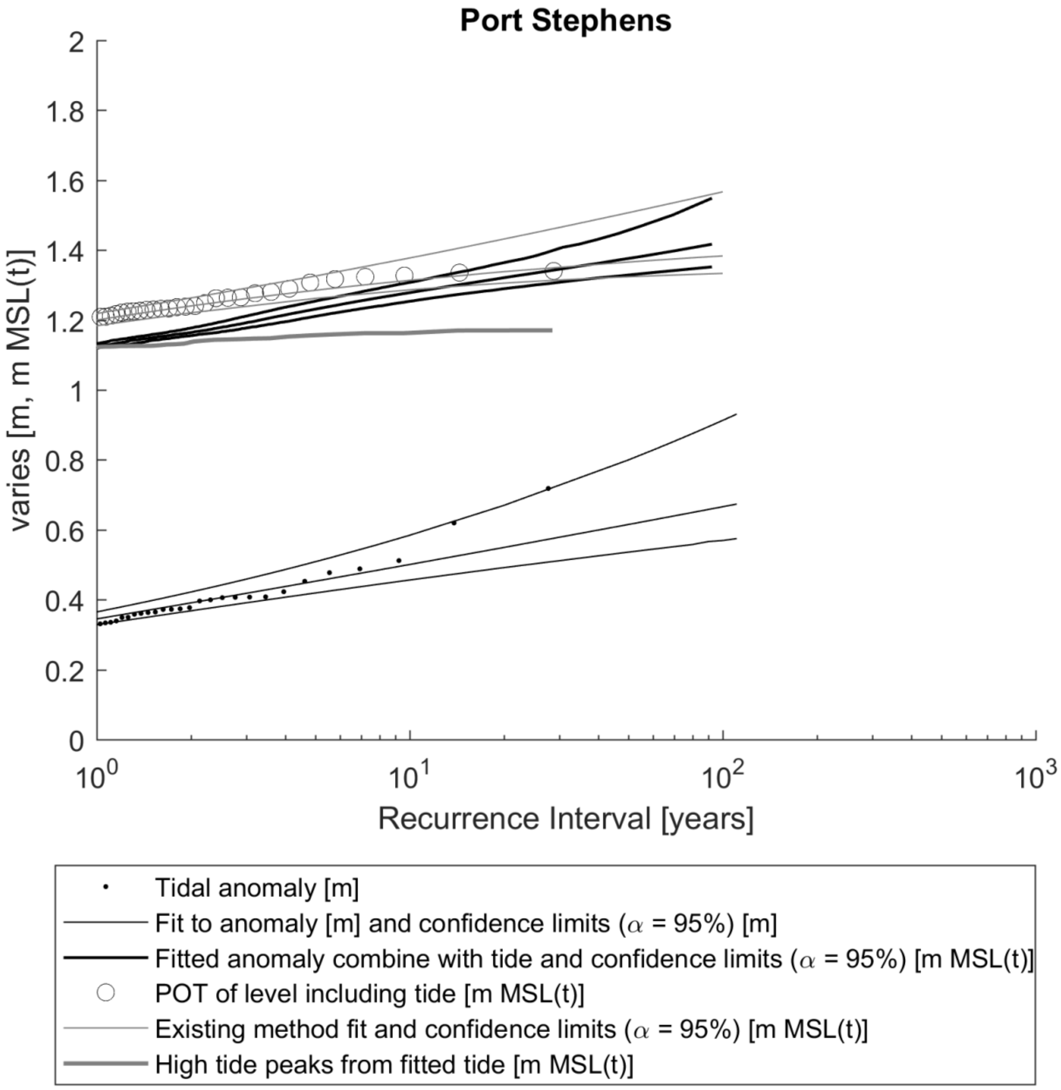


Figure E7.8—Full parametric analysis at Port Stephens. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, 'peak-over-threshold' (data, expectation and confidence limits) and tidal 'extremes' are included.

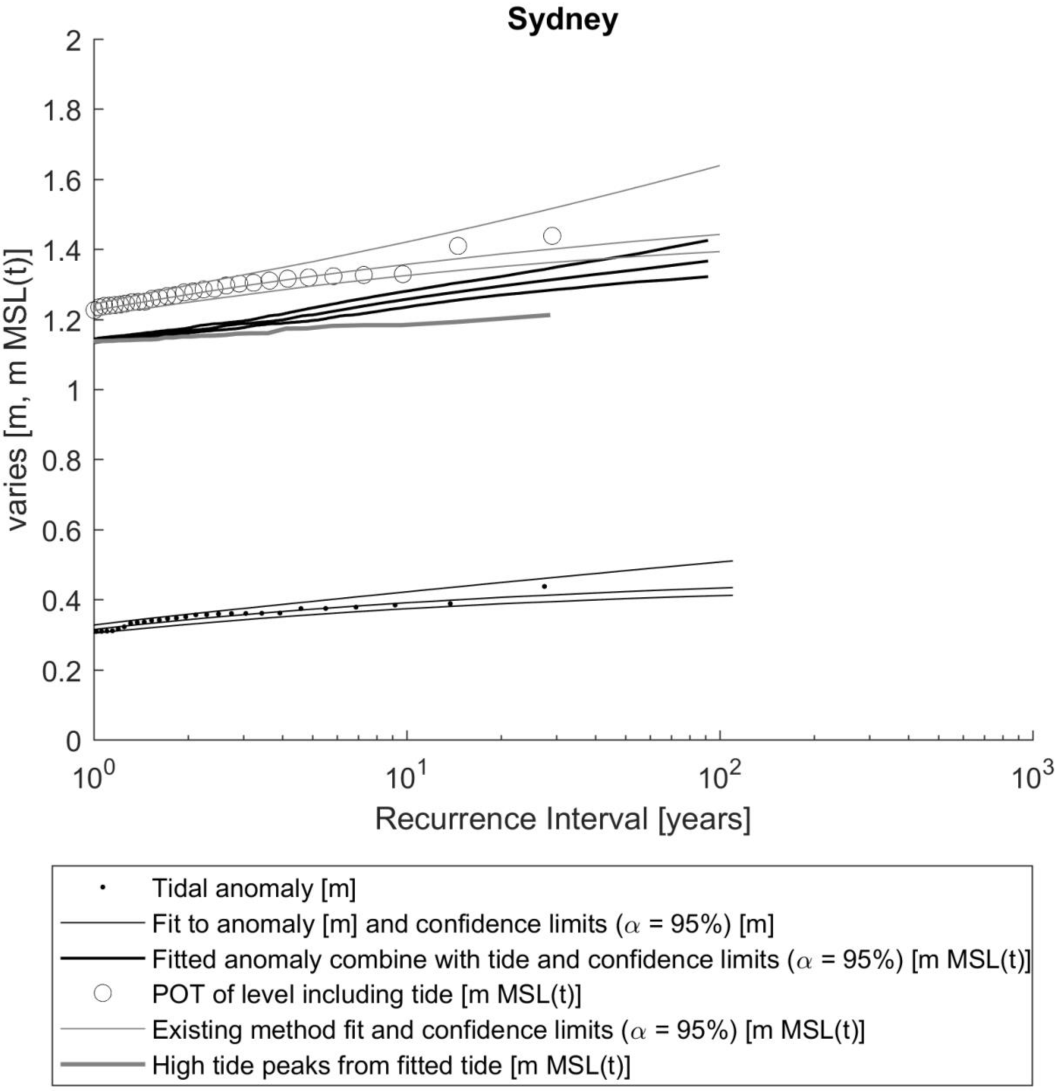


Figure E7.9—Full parametric analysis at Sydney. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, 'peak-over-threshold' (data, expectation and confidence limits) and tidal 'extremes' are included.

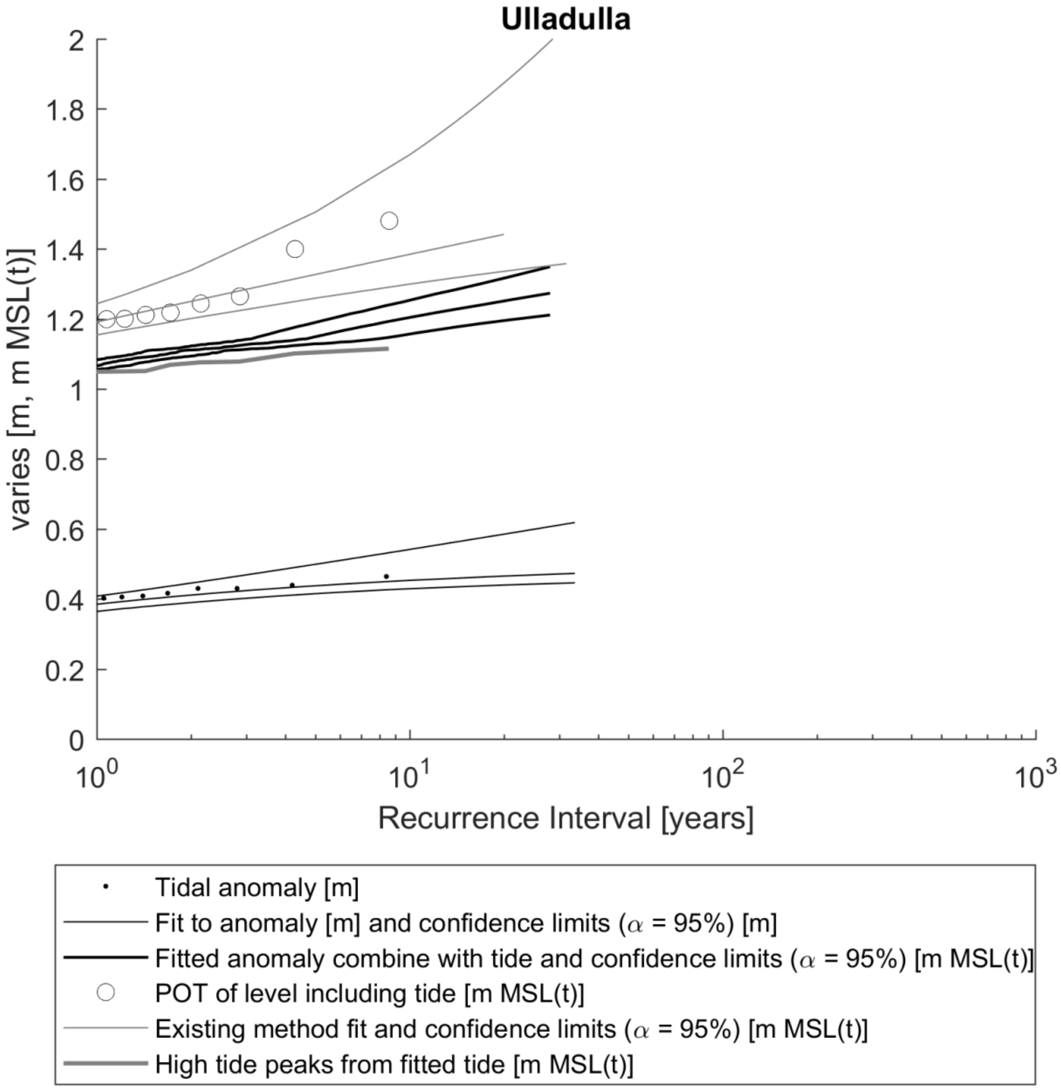


Figure E7.10—Full parametric analysis at Ulladulla. Tidal anomalies fitted to Generalised Pareto distribution and recombined with fitted tide (using variable tidal constituents across one year starting mid-year) by boot strapping including measured duration (weak joint probability). For comparison, 'peak-over-threshold' (data, expectation and confidence limits) and tidal 'extremes' are included.

The '**peak-over-threshold**' method for tidal stations investigated is conservative for frequent events and for infrequent events (e.g., Coffs Harbour above 20-years, Crowdy above 40-years, Eden above 80-years, Patonga above 60-years and Port Stephens above 30-years ARI), underestimates them by about 0.1 m.

The significance of this 'method error' is ±0.1 m and represents the bias from event selection and estimating tidal anomalies compared with other drivers that are effectively ignored in these approaches such as long period tidal constituents (up to 18.6-years), ENSO or IPO.

Modra (2011) investigated the impact from such other drivers by breaking up Fort Denison into 18.61-years, half overlapping data sets, leading to nine distribution estimates. This analysis approach was redone (using more measurements) and for with and without detrending (E11) and including block maxima and peak-over-threshold using water levels and generalised Pareto distribution and an additional peak-over-threshold using water levels that includes joint probability between events using Ferro and Segers (2003) as justified by Fawcett and Walshaw (2012). At the 1-year return period (E11) the impact from de-trending is to reduce the 90th percentile range by approximately half and to shift up estimates (de-trending was applied around the end date). At the 20-year return period (≈18.61 year), up to which measurements are available and without sea level rise, the 90th percentile range was 13 cm (a measure of the impact of nonstationary at the limit of no extrapolation). At 100-year return period, these distributions have a 90th percentile range of 25 cm with different tail shapes, effectively increasing the impact of excluding these drivers on more infrequent estimates (e.g., 49 cm for 1,000-years). This indicates combined uncertainties from these methods and nonstationary processes are of larger magnitude than sampling uncertainties. As a consequence, rules-of-thumbs that suggest extrapolation out to three to five times the record length are invalid as they are based on sampling error arguments. Nevertheless, the underestimation potential when using short analysis with extrapolation of up to five times the length is additionally indicated in this 18.6 year block analysis of Fort Denison with its extrapolation out to 100-year return period.

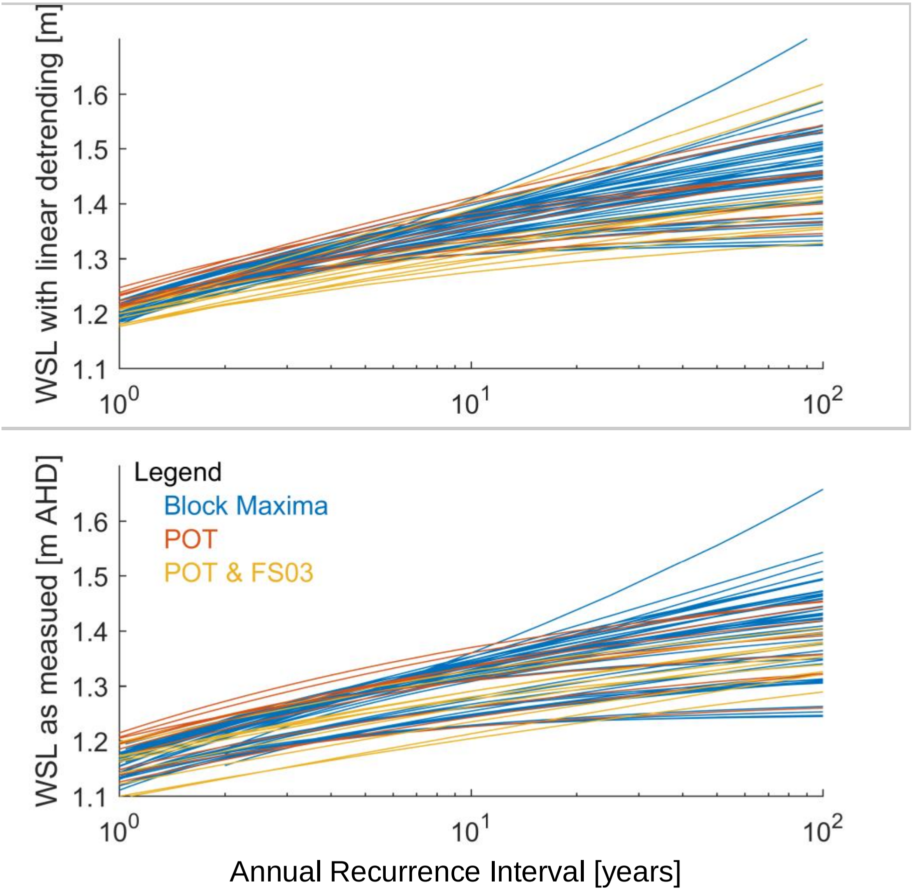


Figure E7.11—Estimated exceedance levels for Fort Denison using as measured water levels (bottom panel) and linear de-trended (top panel) using block maxima (2, 3, 4, 6 & 12 months, blue lines) and peak-over-threshold without (red lines) and with (gold lines) joint probability between events in 18.61-years staggered blocks

It is concluded that extrapolation to 100 years from typical records of only 20 years duration can lead to underestimation of extreme ocean water levels by up to 0.25 m due to other climatic variability (such as ENSO and IPO) and method approaches which may not be represented in the available records. It is suggested that a total factor of safety of 12 cm at 20-year ARI and 25 cm at the 100-year ARI be added to the derived extreme ocean water level distributions adopted for planning and design in NSW to account for uncertainties that potentially range from just enough to 0.25 m overestimate (albeit indeterminable).

For planning and design, additional adjustments for longer term sea level rise would further be required.

References

Anonymous, 2011. WAFO - a Matlab toolbox for analysis of random waves and loads - tutorial for wafo version 2.5. Faculty of Engineering, Centre for Mathematical Sciences, Mathematical Statistics, by the WAFO group, Lund, pp. 185.

Callaghan, D.P., 2008. Coastal hazards, severe storms in New South Wales. Analysis report, Civil Engineering, The University of Queensland, Brisbane.

Ferro, C.A.T. and Segers, J. (2003) Inference for clusters of extreme values. Journal of the Royal Statistical Society: Series B (Statistical Methodology), Vol. 65 No. 2: 545-556.

Folland, C.K., Parker, D.E., Colman, A.W. and Washington, R. (1999) Large Scale Modes of Ocean Surface Temperature Since the Late Nineteenth Century. In: A. Navarra (Editor), Beyond El Niño: Decadal and Interdecadal Climate Variability. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 73-102.

Foster, D.N., Gordon, A.D. and Lawson, N.V., 1975. The storms of May-June 1974, Sydney, N.S.W. Proceedings of the 2nd Australasian Coastal and Ocean Engineering Conference, Gold Coast, Australia, 1-11.

Modra, B., 2011. NSW Ocean Water Levels, Manly Hydraulics Laboratory Report MHL1881.

Appendix F. Updated HAT, LAT and forecasts to 2020

A long-term forecast has been produced for each ocean tide site for the full data range of historical data and predicted to 2020. The methodology determined the average of the yearly constituent values then converted them to a single average phase and amplitude value (including Z_0 or MSL). From these values, a new constituent file was used to predict tidal forecasts up to 2020 (using Foreman analysis). From these forecasts, the Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT) were determined for the epoch of most recent data (1995 to 2014). The values of HAT, LAT and MSL were calculated to local low water datums as well as to AHD and are shown in **Table F1**.

Table F1 Ocean and river entrance tide HAT and LAT values

* AHD offsets given in Table 3.3

Site	Period 1995–2014				Range (HAT-LAT)	Period 1995–2014	
	HAT	LAT	HAT (AHD)*	LAT (AHD)*		MSL	MSL (AHD)*
Tweed Heads	1.99	0.02	1.10	-0.87	1.97	0.93	0.04
Brunswick Heads	1.22	-0.85	1.17	-0.90	2.07	0.07	0.02
Ballina Breakwall	2.02	0.04	1.16	-0.82	1.98	0.89	0.03
Yamba	2.01	0.07	1.12	-0.83	1.94	0.95	0.05
Coffs Harbour	2.12	-0.11	1.24	-0.99	2.23	0.9	0.02
Port Macquarie	1.04	-0.74	1.04	-0.74	1.78	0.02	0.02
Lord Howe Island	2.35	-0.06	n/a	n/a	2.41	1.10	n/a
Norfolk Island	1.97	0.03	n/a	n/a	1.94	0.97	n/a
Crowdy Head	2.1	-0.09	1.19	-1.00	2.19	0.88	-0.03
Forster	1.93	0.17	0.87	-0.89	1.76	1.03	-0.03
Tomaree (Port Stephens)	2.08	-0.03	1.14	-0.97	2.11	0.92	-0.02
Patonga	1.16	-0.88	1.16	-0.88	2.04	0.06	0.06
Sydney	2.07	0.03	1.15	-0.90	2.04	0.96	0.03
Port Hacking	2.11	0.09	1.19	-0.84	2.02	1.00	0.08
Crookhaven Heads	1.01	-0.08	1.01	-0.08	1.09	0.03	0.03
Jervis Bay	2.19	0.10	1.12	-0.97	2.09	1.09	0.02
Ulladulla	0.93	-0.73	0.93	-0.73	1.66	0.04	0.04
Princess Jetty	1.06	-0.79	1.06	-0.79	1.85	0.06	0.06
Bermagui	1.72	-0.18	1.01	-0.89	1.90	0.69	-0.02
Eden	1.92	-0.11	1.00	-1.03	2.03	0.84	-0.08

Mean Sea Level values have been plotted for each site for the periods over which they have been analysed for the Epoch forecasts. These are presented in **Figure F1**.

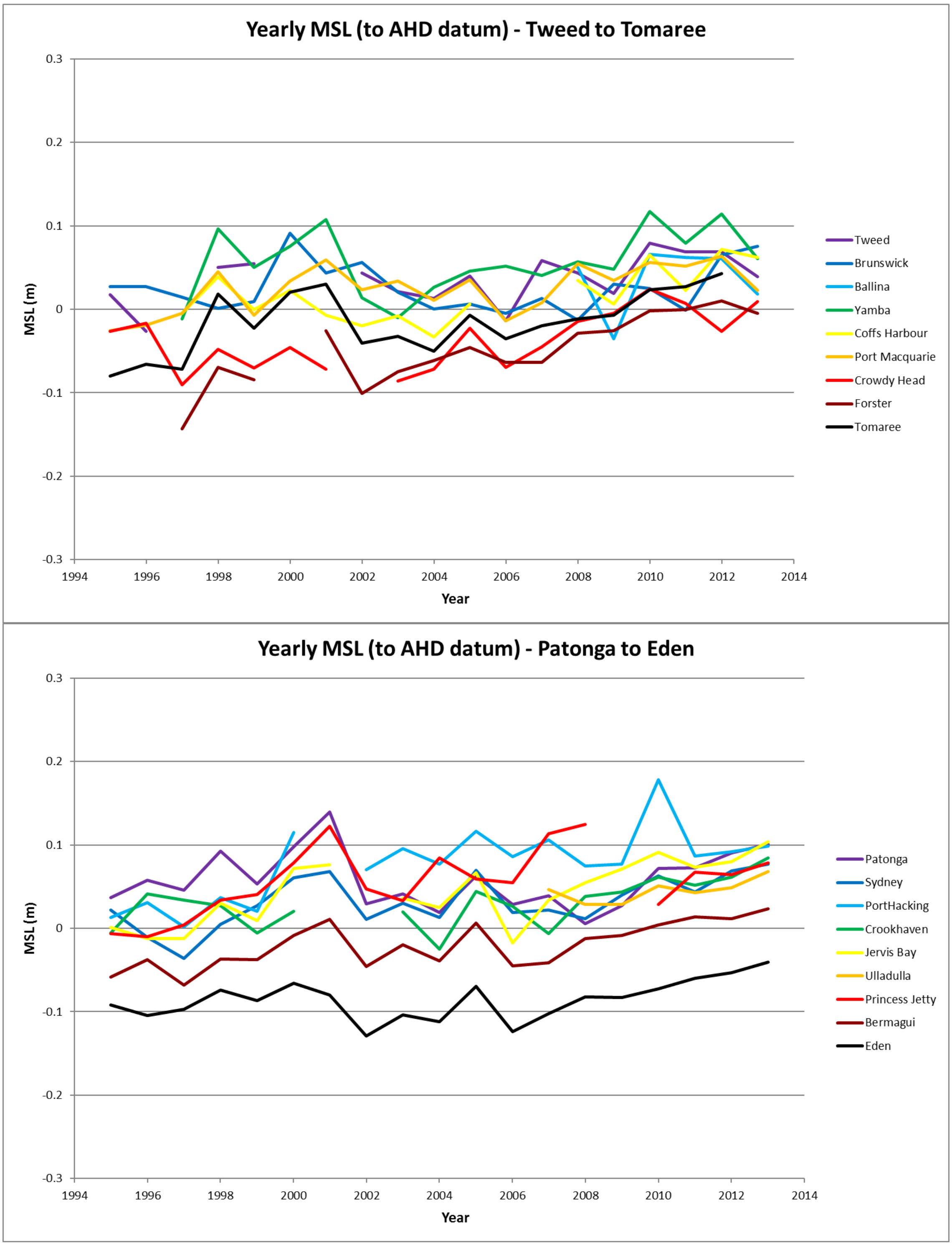
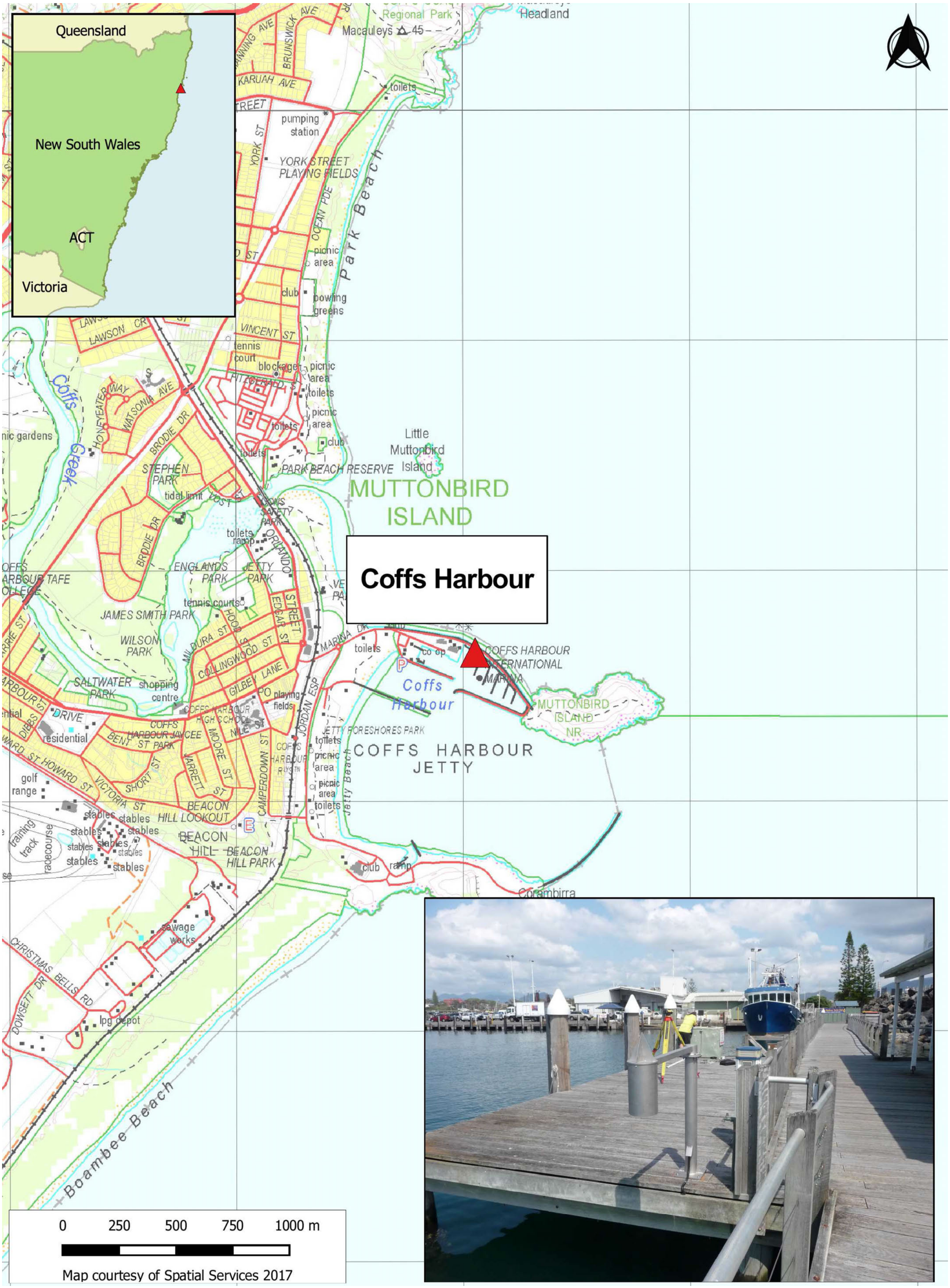


Figure F1 Yearly MSL values to AHD datum along the NSW coastline

Appendix G. Tide gauge location maps



Map courtesy of Spatial Services 2017

STATION LOCATION
Coffs Harbour

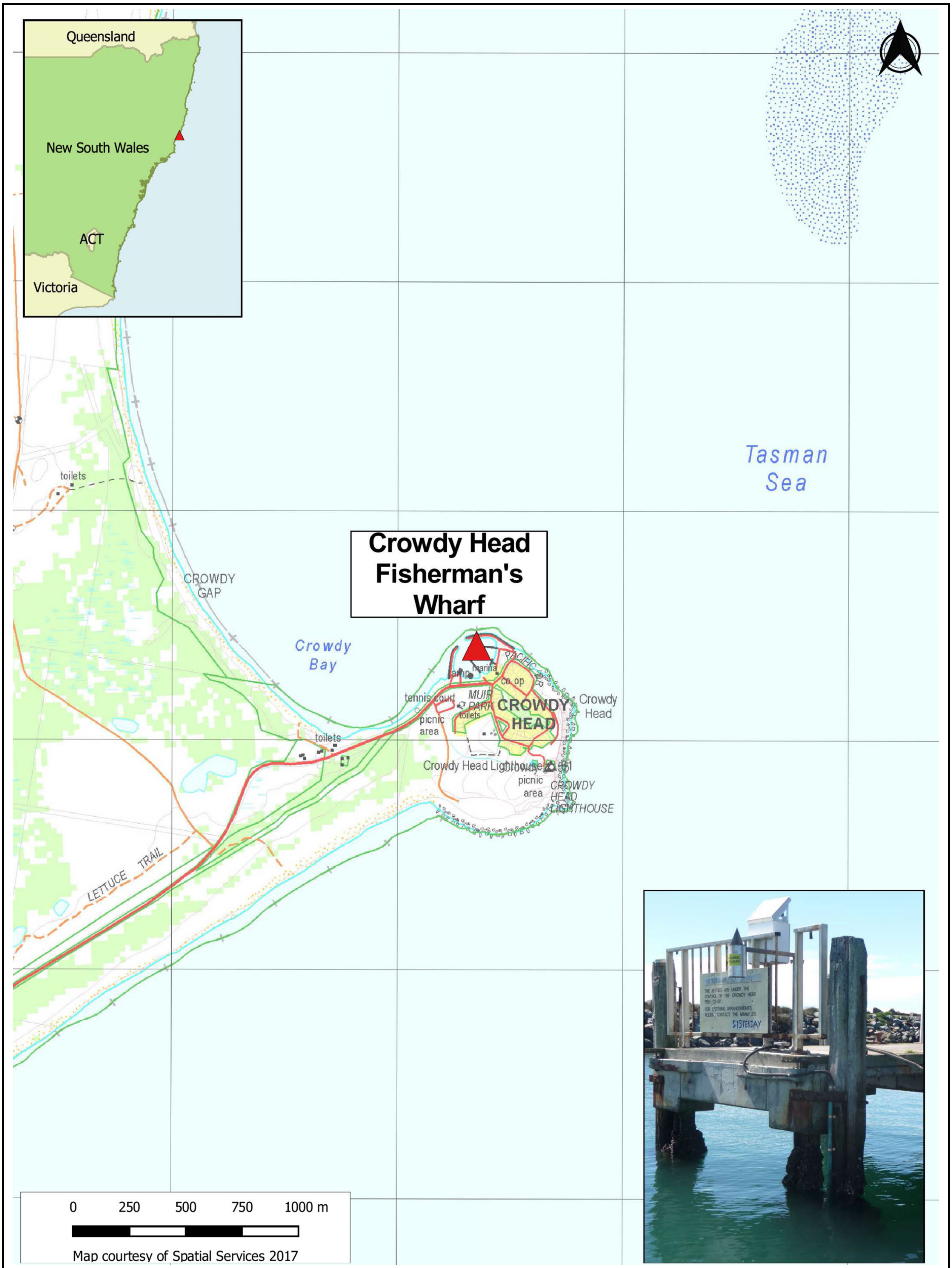
Manly Hydraulics Laboratory

Report MHL2236

Figure

G1

Scale 1:25,000



STATION LOCATION
Crowdy Head Fisherman's Wharf

Manly Hydraulics Laboratory

Report MHL2236
Figure
G2

Scale 1:25,000

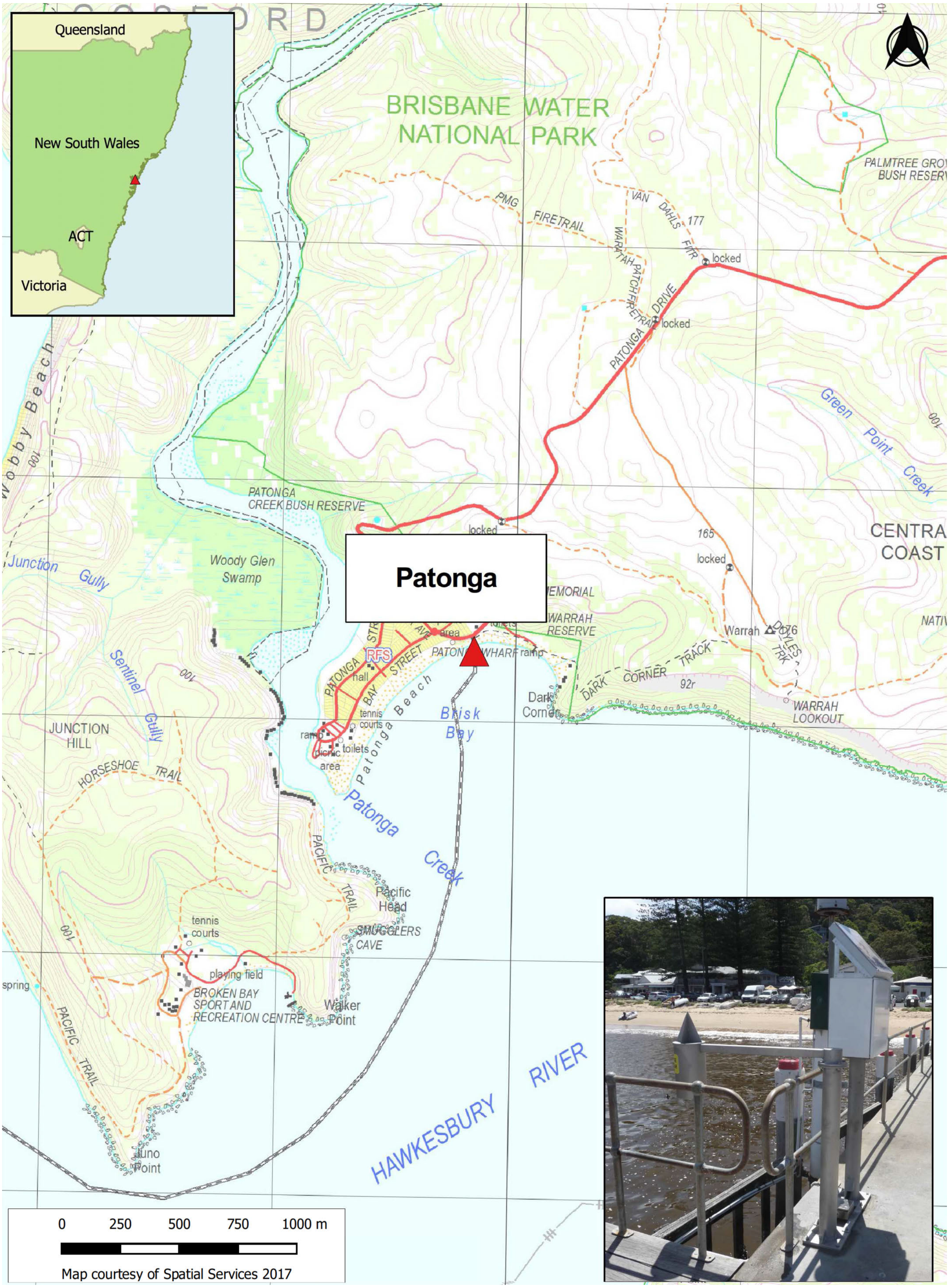
NSW GOVERNMENT

STATION LOCATION
Shoal Bay (Port Stephens)

Manly Hydraulics Laboratory

Report MHL2236
Figure
G3

Scale 1:25,000



STATION LOCATION
Patonga

Manly Hydraulics Laboratory

Report MHL2236
Figure
G4

Scale 1:25,000

Map courtesy of Spatial Services 2017

NSW GOVERNMENT

STATION LOCATION
Fort Denison

Manly Hydraulics Laboratory

Report MHL2236
Figure
G5

Scale 1:25,000

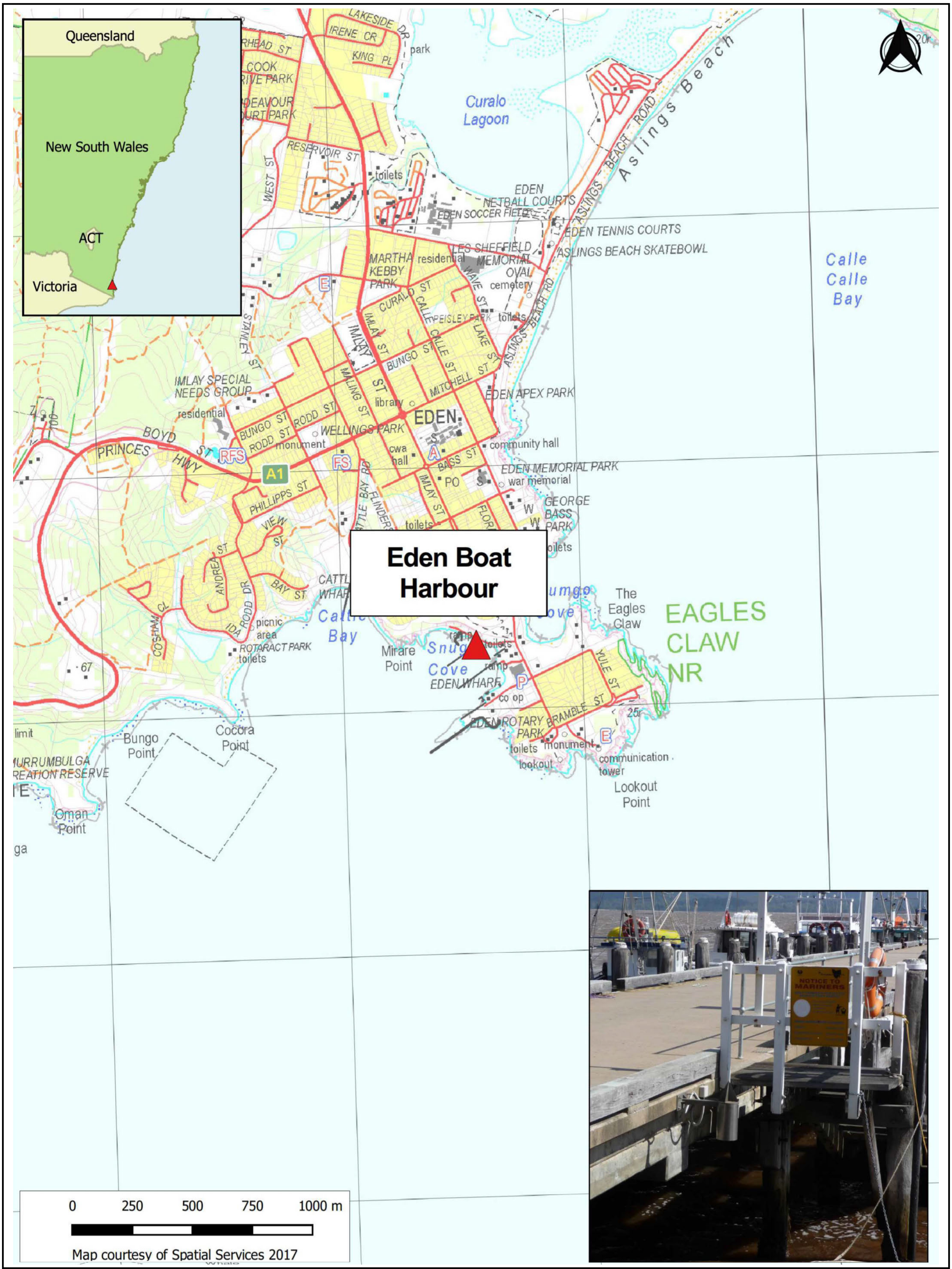
Map courtesy of Spatial Services 2017

STATION LOCATION
HMAS Creswell (Jervis Bay)

Manly
Hydraulics
Laboratory

Report MHL2236
Figure
G6

Scale 1:25,000



Map courtesy of Spatial Services 2017

STATION LOCATION
Eden Boat Harbour

Manly Hydraulics Laboratory

Report MHL2236
Figure
G7

Scale 1:25,000

Appendix H. Glossary of terms

Amplitude (H)	One-half the range of a constituent tide. By analogy, it may be applied also to the maximum speed of a constituent current.
Automatic Tide Gauge	An instrument that automatically registers the rise and fall of the tide. In some instruments, the registration is accomplished by recording the heights at regular time intervals in digital format.
Australian Height Datum (AHD)	The Australian Height Datum is a geodetic datum for altitude measurement in Australia. According to Geoscience Australia, "In 1971 the mean sea level for 1966-1968 was assigned the value of zero on the Australian Height Datum at thirty tide gauges around the coast of the Australian continent. The resulting datum surface, with minor modifications in two metropolitan areas, has been termed the Australian Height Datum (AHD) and was adopted by the National Mapping Council as the datum to which all vertical control for mapping (and other surveying functions) is to be referred.
Benchmark (BM)	A fixed physical object or mark used as reference for a vertical datum. A tidal benchmark is one near a tide station to which the tide staff and tidal datums are referred. A primary benchmark is the principal (or only) mark of a group of tidal benchmarks to which the tide staff and tidal datums are referred.
Chart Datum	The datum to which soundings on a chart are referred. It is usually taken to correspond to a low-water elevation, and its depression below mean sea level is represented by the symbol Z.
Coastal Boundary	The Mean High Water Line (MHWL) or Mean Higher High Water Line (MHHWL) when tidal lines are used as the coastal boundary. Also, lines used as boundaries inland of and measured from (or points thereon) the MHWL or MHHWL.
Constituent	One of the harmonic elements in a mathematical expression for the tide-producing force and in corresponding formulas for the tide or tidal current. Each constituent represents a periodic change or variation in the relative positions of the earth, moon and sun. A single constituent is usually written in the form y = A cos (at + á), in which y is a function of time as expressed by the symbol t and is reckoned from a specific origin. The coefficient A is called the amplitude of the constituent and is a measure of its relative importance. The angle (at + á) changes uniformly and its value at any time is called the phase of the constituent. The speed of the constituent is the rate of change in its phase and is represented by the symbol a in the formula. The quantity a is the phase of the constituent at the initial instant from which the time is reckoned. The period of the constituent is the time required for the phase to change through 360° and is the cycle of the astronomical condition represented by the constituent.
Digital	An electronic recorder system which stores the information in accessible

Recorder (or logger)	form, for example, on tape or solid state memory.
Digitise	To translate analog information into digital form i.e. a series of numeric data readable by, and stored within, a digital computer.
Diurnal	Having a period or cycle of approximately one tidal day. Thus, the tide is said to be diurnal when only one high water and one low water occur during a tidal day, and the tidal current is said to be diurnal when there is a single flood and a single ebb period of a reversing current in the tidal day. A rotary current is diurnal if it changes its direction through all points of the compass once each tidal day. A diurnal constituent is one which has a single period in the constituent day. The symbol for such a constituent is the subscript 1.
Encoder	A device that translates tidal movement into computer readable data.
Estuary	An embayment of the coast in which fresh river water entering at its head mixes with the relatively saline ocean water. When tidal action is the dominant mixing agent it is usually termed a tidal estuary. Also, the lower reaches and mouth of a river emptying directly into the sea where tidal mixing takes place. The latter is sometimes called a river estuary.
Extreme High Water	The highest elevation reached by the sea as recorded by a tide gauge during a given period.
Extreme Low Water	The lowest elevation reached by the sea as recorded by a tide gauge during a given period.
Floatwell	A stilling well in which the float of a float-actuated gauge operates.
Gas Purged Pressure Gauge	A type of analog tide gauge in which gas, usually nitrogen, is emitted from a submerged tube at a constant rate. Fluctuations in hydrostatic pressure due to changes in tidal height modify the emission rate for recording.
Harmonic Analysis	Process of measuring or calculating the relative amplitudes and frequencies of all the significant harmonic components present in a given wave form.
Harmonic Prediction	Method of predicting tides by combining the harmonic constituents into a single tidal curve. The work is usually performed by electronic digital computer.
Head	The difference in water level at either end of a strait, channel, inlet, etc.
High Water (HW)	The maximum height reached by a rising tide. The high water is due to the periodic tidal forces and the effects of meteorological, hydrologic, and/or oceanographic conditions. For tidal datum computational purposes, the maximum height is not considered a high water unless it contains a tidal high water.
High Water Mark	A line or mark left upon tide flats, beach, or alongshore objects indicating the elevation of the intrusion of high water. The mark may be a line of oil or scum on alongshore objects, or a more or less continuous deposit of fine shell or debris on the foreshore or berm. This mark is physical evidence of the general height reached by wave runup at recent high waters. It should not

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	be confused with the Mean High Water Line or Mean Higher High Water Line.
Higher High Water (HHW)	The highest of the high waters (or single high water) of any specified tidal day due to the declination A_l effects of the moon and sun.
Higher Low Water (HLW)	The highest of the low waters of any specified tidal day due to the declination A_l effects of the moon and sun.
Highest Astronomical Tide (HAT)	The highest level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions; this level will not be reached every year. HAT is not the extreme level which can be reached as storm surges may cause considerably higher levels to occur.
Hydrographic Datum	A datum used for referencing depths of water and the heights of predicted tides or water level observations. Same as Chart Datum. See Datum.
ICOLL	Intermittently closed or open (coastal) lakes and lagoons
Indian Spring Low Water	A datum originated by Professor G. H. Darwin when investigating the tides of India. It is an elevation depressed below mean sea level by an amount equal to the sum of the amplitudes of the harmonic constituents M_2, S_2, K_1, and O_1.
Inverse Barometer Effect	The inverse response of sea level to changes in atmospheric pressure. A static reduction of 1.005 mb in atmospheric pressure will cause a stationary rise of 1 cm in sea level.
K_1	Lunisolar diurnal constituent. This constituent, with O_1, expresses the effect of the moon's declination. They account for diurnal inequality and, at extremes, diurnal tides. With P_1, it expresses the effect of the sun's declination. Speed = T + h = 15.041,068,6° per solar hour.
Lambda	Smaller lunar evectional constituent. This constituent, with V_2, U_2, and (S_2), modulates the amplitude and frequency of M_2 for the effects of variation in solar attraction of the moon. This attraction results in a slight pear-shaped lunar ellipse and a difference in lunar orbital speed between motion toward and away from the sun. Although (S_2) has the same speed as S_2, its amplitude is extremely small. Speed = 2T - s + p = 29.455,625,3° per solar hour.
Low Water (LW)	The minimum height reached by a falling tide. The low water is due to the periodic tidal forces and the effects of meteorological, hydrologic, and/or oceanographic conditions. For tidal datum computational purposes, the minimum height is not considered a low water unless it contains a tidal low water.
Lower High Water (LHW)	The lowest of the high waters of any specified tidal day due to the declination A_l effects of the moon and sun.
Lower Low Water (LLW)	The lowest of the low waters (or single low water) of any specified tidal day due to the declination A_l effects of the moon and sun.

Lowest Astronomical Tide (LAT)	The lowest level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions; this level will not be reached every year. LAT is not the extreme level which can be reached as storm surges may cause considerably lower levels to occur.
Lunar Tide	That part of the tide on the earth due solely to the moon as distinguished from that part due to the sun.
Magnetic Tape	Recording tape on which (numeric) data may be stored.
M_2	Principal lunar semi-diurnal constituent. This constituent represents the rotation of the Earth with respect to the Moon. Speed = 2T - 2s + 2h = 28.984,104,2° per solar hour.
M_{sf}	Lunisolar synodic fortnightly constituent. Speed = 2s - 2h = 1.015,895,8° per solar hour.
Mean High Water (MHW)	A tidal datum. The average of all the high water heights observed over the National Tidal Datum Epoch. For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum.
Mean High Water Neaps (MHWN)	The average of high water heights occurring at the time of neap tides.
Mean High Water Springs (MHWS)	The average of high water heights occurring at the time of spring tides.
Mean Low Water (MLW)	The average of all low water heights observed over a period.
Mean Low Water Neaps (MLWN)	The average of the low water heights occurring at the time of neap tides.
Mean Low Water Springs (MLWS)	A tidal datum. Frequently abbreviated spring low water. The arithmetic mean of the low water heights occurring at the time of spring tides observed over the National Tidal Datum Epoch. It is usually derived by taking an elevation depressed below the half-tide level by an amount equal to one-half the spring range of tide, necessary corrections being applied to reduce the result to a mean value.
Mean Range of Tide (Mn)	The difference in height between Mean High Water and Mean Low Water.
Modem	A device allowing a computer to be accessed over a telephone line.
Neap Tides	Tides of decreased range or tidal currents of decreased speed occurring semi-monthly as the result of the moon being in quadrature. The neap range

	(Np) of the tide is the average range occurring at the time of neap tides and is most conveniently computed from the harmonic constants. It is smaller than the mean range where the type of tide is either semi-diurnal or mixed and is of no practical significance where the type of tide is predominantly diurnal. The average height of the high waters of the neap tide is called Neap High Water or High Water Neaps (MHWN) and the average height of the corresponding low waters is called Neap Low Water or Low Water Neaps (MLWN).
O_1	Lunar diurnal constituent. See K_1. Speed = T - 2s + h = 13.943,035,6° per solar hour.
Phase	Any recurring aspect of a periodic phenomenon, such as new moon, high water, flood strength, etc. A particular instant of a periodic function expressed in angular measure and reckoned from the time of its maximum value, the entire period of the function being taken as 360°. The maximum and minimum of a harmonic constituent have phase values of 0° and 180°, respectively.
Pressure Sensor	A pressure transducer sensing device for water level measurement. A relative transducer is vented to the atmosphere and pressure readings are made relative to atmospheric pressure. An absolute transducer measures the pressure at its location. The readings are then corrected for barometric pressure taken at the surface.
Range of Tide	The difference in height between consecutive high and low waters. The mean range is the difference in height between mean high water and mean low water. The great diurnal range or diurnal range is the difference in height between mean higher high water and mean lower low water.
Relative Mean Sea Level Change	A local change in mean sea level relative to a network of benchmarks established in the most stable and permanent material available (bedrock, if possible) on the land adjacent to the tide station location. A change in relative mean sea level may be composed of both an absolute mean sea level change component and a vertical land movement change component, together.
S_2	Principal solar semi-diurnal constituent. This constituent represents the rotation of the Earth with respect to the Sun. Speed = 2T = 30.000,000,0° per solar hour.
Seiche	A stationary wave usually caused by strong winds and/or changes in barometric pressure. It is found in lakes, semi-enclosed bodies of water, and in areas of the open ocean. The period of a seiche in an enclosed rectangular body of water is usually represented by the formula : Period (T) = 2L / square root (gd) in which L is the length, d the average depth of the body of water, and g the acceleration of gravity.
Semi-Diurnal	Having a period or cycle of approximately one-half of a tidal day. The predominant type of tide throughout the world is semi-diurnal, with two high waters and two low waters each tidal day. The tidal current is said to be semi-

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	diurnal when there are two flood and two ebb periods each day. A semi-diurnal constituent has two maxima and two minima each constituent day, and its symbol is the subscript 2.
Shallow Water Constituent	A short-period harmonic term introduced into the formula of tidal (or tidal current) constituents to take account of the change in the form of a tide wave resulting from shallow water conditions. Shallow water constituents include the overtides and compound tides.
Slack Water (Slack)	The state of a tidal current when its speed is near zero, especially the moment when a reversing current changes direction and its speed is zero. The term also is applied to the entire period of low speed near the time of turning of the current when it is too weak to be of any practical importance in navigation. The relation of the time of slack water to the tidal phases varies in different localities. For a perfect standing tidal wave, slack water occurs at the time of high and of low water, while for a perfect progressive tidal wave, slack occurs midway between high and low water.
Solar Tide	1. The part of the tide that is due to the tide-producing force of the sun. 2. The observed tide in areas where the solar tide is dominant. This condition provides for phase repetition at about the same time each solar day.
Solid State	An electronic device composed of components with no moving parts - in this instance, using the electronic properties of solids, as in transistors, semi-conductors and integrated circuits.
Spring High Water	Same as Mean High Water Springs (MHWS). See Spring Tides.
Spring Low Water	Same as Mean Low Water Springs (MLWS). See Spring Tides and Mean Low Water Springs.
Spring Tides	Tides of increased range or tidal currents of increased speed occurring semi-monthly as the result of the moon being new or full. The spring range (Sg) of tide is the average range occurring at the time of spring tides and is most conveniently computed from the harmonic constants. It is larger than the mean range where the type of tide is either semi-diurnal or mixed, and is of no practical significance where the type of tide is predominantly diurnal. The average height of the high waters of the spring tides is called Spring High Water or Mean High Water Springs (MHWS) and the average height of the corresponding low waters is called Spring Low Water or Mean Low Water Springs (MLWS).
Storm Surge	The local change in the elevation of the ocean along a shore due to a storm. The storm surge is measured by subtracting the astronomic tidal elevation from the total elevation. It typically has a duration of a few hours. Since wind generated waves ride on top of the storm surge (and are not included in the definition), the total instantaneous elevation may greatly exceed the predicted storm surge plus astronomic tide. It is potentially catastrophic, especially on

	low-lying coasts with gently sloping offshore topography.
Telemeter	Transmit data to a distant receiving station via a telephone line or by telegraphic means.
Tidal Anomaly	The difference between the recorded and predicted tide level generally representative of the non-astronomical factors influencing coastal water levels such as storm surge.
Tidal Characteristics	Principally, those features relating to the time, range, and type of tide.
Tidal Constants	Tidal relations that remain practically constant for any particular locality. Tidal constants are classified as harmonic and non-harmonic. The harmonic constants consist of the amplitudes and epochs of the harmonic constituents, and the non-harmonic constants include the ranges and intervals derived directly from the high and low water observations.
Tidal Current	A horizontal movement of the water caused by gravitational interactions between the Sun, Moon and Earth. The horizontal component of the particulate motion of a tidal wave. Part of the same general movement of the sea that is manifested in the vertical rise and fall called tide.
Tidal Limit	That point along a tidal estuary above which there is no tidal influence.
Tide	The periodic rise and fall of the water resulting from gravitational interactions between Sun, Moon and Earth. The vertical component of the particulate motion of a tidal wave. Although the accompanying horizontal movement of the water is part of the same phenomenon, it is preferable to designate this motion as tidal current.
Tide Curve	A graphic representation of the rise and fall of the tide in which time is usually represented by the abscissa and height by the ordinate. For a semi-diurnal tide with little diurnal inequality, the graphic representation approximates a cosine curve.
Tide (Water Level) Gauge	An instrument for measuring the rise and fall of the tide (Water Level).
Tide Tables	Tables which give daily predictions of the times and heights of high and low waters. These predictions are usually supplemented by tidal differences and constants through which predictions can be obtained for numerous other locations.
Tsunami	A shallow water progressive wave, potentially catastrophic, caused by an underwater earthquake or volcano.
Universal Time (UTC)	Same as Greenwich Mean Time (GMT).
Z_0	Symbol recommended by the International Hydrographic Organisation to represent the elevation of mean sea level above chart datum.