Appendix B Inundation and Water Level Analysis

B.1 Overview

In Planning for potential future inundation events there are four main components that are generally considered:

- Astronomical Tidal stage (i.e. high tide)
- Relative SLR (i.e. due to climate change or ground level change)
- Storm surge (combined effects of barometric pressure and wind setup effects)
- Wave setup/runup.

B.2 Southern NSW Wave climate and storms

On average, the study area experiences a moderate to high energy wave climate, it is exposed to a mean H_s of 1.6m (with T_p= 10 s) that originates principally from the southsoutheast, as swell waves (Short and Trenaman 1992; Turner *et al.* 2016). Superimposed on these background swell waves are storm events, which are distinguished by being over 3 m in significant wave height (Harley *et al.* 2010). These storm waves are also derived from several cyclonic systems, for southern NSW (which is where the study site is situated), the key systems producing major storm events include a combination of East coast cyclones (inc. Easterly Trough Lows), Midlatitude cyclones (from the south) and Mainland low pressure systems (Shand *et al.* 2011; Turner *et al.* 2016; Doyle 2019).

Previous studies have also shown that at inter-annual time scales, the wave climate can also be influenced by the El Niño/Southern Oscillation (ENSO) (Harley *et al.* 2011; Barnard *et al.* 2015), with La Niña periods producing a more energetic easterly wave climate, as opposed to El Niño periods, which typically produce less energetic, and more southerly wave climates. El Niño periods of the ENSO have been shown to also be associated with intense storm activity, which has increased in intensity in recent years, and has corresponded with large beach erosion, especially across the US West Coast (Barnard *et al.* 2017; Doyle, 2019).

It is important to understand wind and wave processes, as they are key drivers influencing sediment transport mechanisms on the coast, and hence needs to be considered when investigating coastal hazards. For example, while storm waves often produce devastating instantaneous damage and beach-dune erosion, the normal / calmer (or ‘ambient’) wave climate that continues post-storm is what is responsible for the beach and dune recovery, longer-term sediment delivery and shoreline orientation (i.e. swell waves bring sand back) (Ranasinghe *et al.* 2004; Harley *et al.* 2011; Mortlock and Goodwin 2015).

B.3 Astronomic Tide

Tidal variation is the most easily observed variation in ocean water levels in most areas of the coast. Gravitational changes due to the rotating earth, sun and moon (and other ‘astronomic’ bodies) create a forcing on the oceans, which interact with local geographic features and create the resonances we refer to as ‘tide’.

Along the east coast of Australia, the tides typically follow a semi-diurnal (twice daily) pattern with two high tides and two low tides per day, corresponding to the rotation of the moon around the earth. As the position of the moon relative to the sun changes on a monthly scale (as seen in the phases of the moon), these high and low tides change in their amplitude throughout the month. This pattern is commonly known as the spring/neap cycle, with the spring tides occurring during the full and new moons when the sun and moon gravitational effects align, leading to the highest high-tides, and lowest low-tides at an approximately 14-day interval. Longer-term effects can also occur that relate to specific influences of the eccentricity of orbits and/or the relative angles of orbit to the earth's axis. While much smaller than the semi-diurnal or the spring/neap effects, these can increase/decrease the tidal amplitudes over annual, or even less-frequent scales.

Astronomical tide effects can be used for tide prediction by calculating the relative amplitude and timing (phase) of each of these forcing components (constituents) using astronomic tidal analysis. This analysis is conducted by analysing tidal water level gauges and attempting to remove any non-astronomic effects. Relatively high-quality estimates can be derived from long-term tide gauges and key levels (tidal planes) can be reported. Table B-1 presents key tidal planes taken from.

Table B-1 Tidal Planes at Fort Denison

Name	Description	Level (m MSL)	Source
HAT	Highest Astronomical Tide. The potential combination of all astronomic components. i.e. the highest astronomic high-tide possible.	1.15	MHL (2017)
MHWS	Mean High Water Springs. The average high tide during spring tides.	0.64	MHL (2018)
MHW	Mean High Water. The average of all high tides.	0.51	
MHWN	Mean High Water Neaps. The average high tide during neap tides.	0.39	

B.4 Sea Level Rise

A relative shift in all ocean water levels can occur for several reasons. The first is a change in the ground level due to geological effects. These effects are usually small, but localised areas may experience significant changes due to effects from the prevailing geology. The second is observed SLR due to ongoing climate change.

A warming climate can impact sea levels for a number of reasons. Study of climate science has largely focussed on increased ocean water due to meltwater (melting glaciers and ice-sheets), expansion of seawater due to temperature increase, and glacial isostatic adjustment (the rebounding or sinking of the earth's crust as the mass of glaciers is removed). Many of these effects are known to have occurred in the geological past (through cyclical ice-ages) and are responsible for some of the geological features of current coastlines. The Intergovernmental Panel on Climate Change (IPCC) is the most widely recognised body that disseminates objective science on climate change and its associated impacts. The IPCC has released several documents that detail the state of the current science, the latest of which is the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2019). The SROCC details the following conclusions:

- Mean sea level has risen globally throughout that 20th century and has accelerated in recent decades.
- Total mean SLR from 1902 to 2015 is 0.16 m (likely range of 0.12-0.21 m).
- The rate of SLR over 2006-2015 is 3.6 mm/year (very likely range of 3.1-4.1 mm/year).
- The Greenland and Antarctic ice sheets are predicted to lose mass at an increasing rate throughout the 21st century.

- Strong reductions in greenhouse gas emissions in the coming decades are required in order to reduce further changes after 2050.

These projected changes (last two points) are based on a range of different global climate models that simulate several potential future scenarios of carbon emissions. These different scenarios are known as *Representative Concentration Pathways* (RCPs). While it is currently difficult to predict the pathway that the global society will ‘adopt’ over the longer-term, these different RCPs provide suitable pathways to quantify potential impacts that would result for each one. As each RCP is simulated by a range of different models that use slightly different underlying numerical methodologies and assumptions, the SROCC details a range of potential values in its projections of SLR through to 2100. The IPCC provides the average of these, as well as a 5-95% confidence interval range.

For the purpose of coastal management planning in east coast Australia, it is suitable at this stage to adopt the most conservative RCP8.5. This represents a ‘business as usual’ pathway where limited success is achieved in reducing global carbon emissions. In the context of inundation risk, this represents SLR constantly accelerating throughout the 21st century and continuing to accelerate beyond 2100.

It should be noted that the SLR projections of the different RCPs are relatively similar prior to 2050, reducing the sensitivity for near-future planning horizons. With such potential catastrophic consequences, planning for excessive risk earlier is likely to be more cost-effective than insufficiently planning and requiring emergency mitigations with less time. As such, beyond 2050 it is more suitable to adopt the conservative ‘upper-bound’ values to prepare for longer-term mitigation/adaptation needs and revise down later if needed. It is therefore recognised that all assumptions based on SLR projections should be updated in the coming decades as the effects of the global effort to reduce emissions become clearer and as climate science is advanced.

B.5 Open Coast Extreme Sea Levels

Ocean water levels can be increased or decreased relative to the notional astronomic tide level by local (non-planetary) forces.

The most noticeable of these are those due to mesoscale and synoptic scale weather system such as different types of storms. In NSW, there are several modes of storms that commonly affect ocean water levels with subtle differences in their spatial scales, temporal scales and intensities (such as extra-tropical cyclones, east coast lows or tornados). Storms influence sea levels in two ways:

(1) By air pressure differences either lifting (low air pressure) or depressing (high air pressure) the ocean surface with the inverse barometer effect.

(2) By increased winds due to storm conditions creating a stress on the water surface that pushes water along, creating a so-called ‘setup’ in the direction that more water is being pushed, and a corresponding ‘set down’ in its wake. These effects are highly dependent on the wind direction and fetch length, as well as the nearby topographic features.

Beyond storms, other processes can have short-term impacts on sea-levels, such as geological releases of energy in earthquakes and landslips, or higher-order resonances of wind-waves, distant storms and seismic effects that interact with the continental shelf and the coastline (i.e. submarine landslides).

These processes are all studied by using ‘Extreme Value Analysis’ (EVA). This methodology uses past observations of processes in an area to define a relationship between the magnitude of an event and its frequency. After a certain point (beyond normal tidal ranges), increasingly higher water levels occur at less and less frequent intervals. It is often the case that different 'modes' dominate different frequency ranges. For example in NSW, tidal water levels dominate the highest water levels expected in a typical day or week, mild storms may dominate over a monthly scale, and significant east-coast low conditions may dominate conditions that occur less frequently (once-in-a-generation events). Storms that persist longer than a tidal cycle are guaranteed to occur with at least one high-tide and therefore result in increases above astronomic tidal levels.

A fundamental problem with assessing the impacts of extreme events is that by their nature they are rare. It is therefore uncertain whether the largest event/s observed over a 100-year period (for example) is a 1-in-100-year event, or whether that century was abnormally calm or extreme relative to an even longer-term record. It is also the case that the dominant modes and their associated magnitudes may increase or decrease over time (e.g. due to climate change) or operate in cycles of intensity over geological time-scales.

Notwithstanding these uncertainties, longer-term datasets tend to provide robust estimates of extreme conditions. In the NSW context, the overall uncertainties in extreme water levels are lower than the uncertainties in future SLR at this time. The NSW Extreme Ocean Water Levels report (MHL 2018) investigated anomalies (extreme sea levels) recorded on the NSW coast and their occurrence and forcing mechanisms.

For this study, observed extreme tidal water levels at the Fort Denison tide recorded have been analysed from 1965 to 2019. A peak-over-threshold (PoT) methodology was used to extract extreme events classed as water level peaks above 1 mAHD separated by a minimum 6-day period. These extremes have been fitted to a generalised pareto distribution for extrapolation. For each given ARI, the uncertainty bounds represent the 5-95 percentile range from a normal distribution around the mean. The results are shown in Figure B-1 and Table B-2.

Table B-2 Extreme Value Results at Fort Denison

Frequency (ARI)	Water Level Best Fit (m) (5-95% CI)
1-year	1.21 (1.19 – 1.22)
10-year	1.35 (1.32 – 1.37)
20-year	1.38 (1.35 – 1.41)
50-year	1.41 (1.38 – 1.44)
100-year	1.43 (1.39 – 1.47)

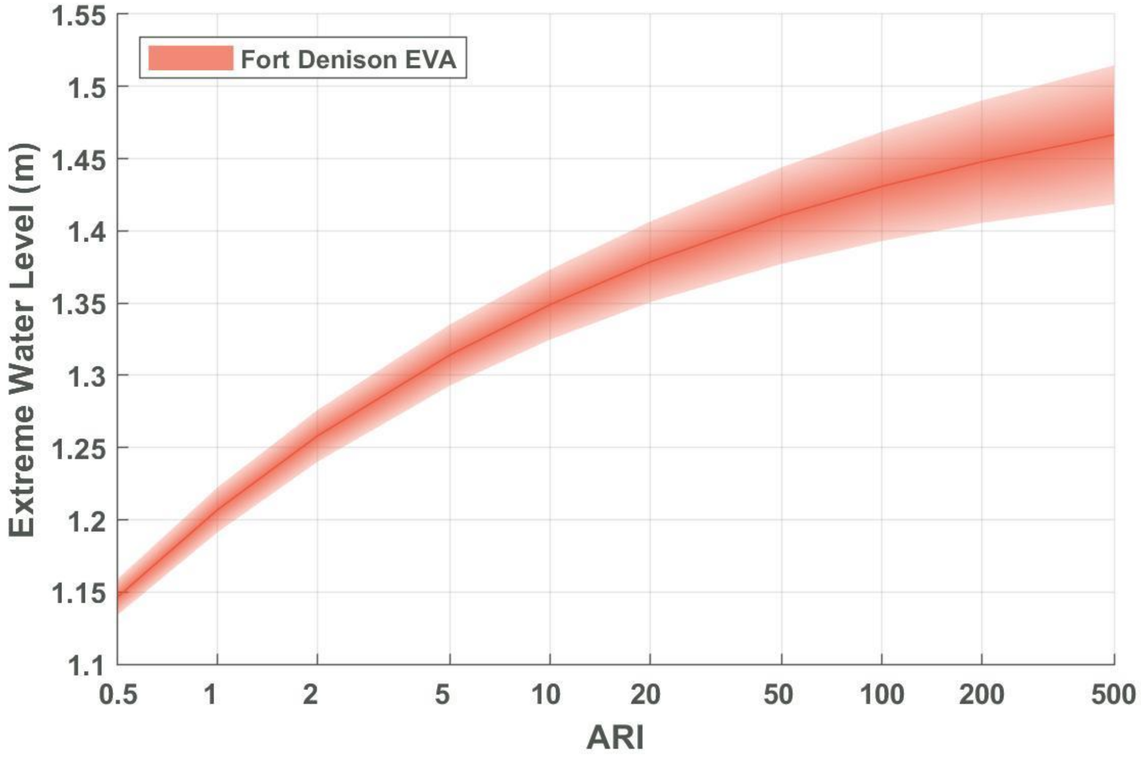

Figure B-1 Extreme Value Analysis at Fort Denison (5-95% CI shown)

B.6 Wave Setup/Runup

As wind waves approach the coast, they break and cause a release of the wave energy. This process generally serves to push water towards the shoreline, increasing water levels. There are two main components of this, a wave ‘setup’ associated with an increase in mean water levels near the coast due to breaking waves, and the wave ‘runup’, which is the effect of individual broken waves washing up the beach slope as swash.

These effects are very difficult to model accurately, with most methods deriving from empirical observations. The true effects change with each successive wave, and so are usually expressed as either the ‘maximum’ wave runup/setup effect or the 2% exceedance level over a given time period. Most empirical methods relate the wave runup to the wave height, wavelength (related to wave period) and the slope of the beach face at the water level.

In assessing wave setup/runup effects for Kiama, the model of Stockdon et al. has been applied (Stockdon, Holman, Howd, & Sallenger, 2006). This relates an extreme significant wave height and wavelength with the relevant beach slope to calculate components of both the wave setup and runup based on the following formula:

$$H_{2\%} = 1.1 \times \left(0.35 \tan \beta \sqrt{H_0 L_0} + \frac{\sqrt{H_0 L_0 (0.563 \tan \beta^2 + 0.004)}}{2} \right)$$

Where β is the average slope over ±2 times the standard deviation of water level elevation (generally the intertidal region). This is the most variable as under extreme conditions this region may be eroding and changing rapidly. Based on analysis of the 2018 Marine LiDAR, many of the beaches within the Kiama coastline have a beach slope in this region less than 0.1. As such, tanβ=0.1 (1:10) has been taken as a suitable approximation for beach slope.

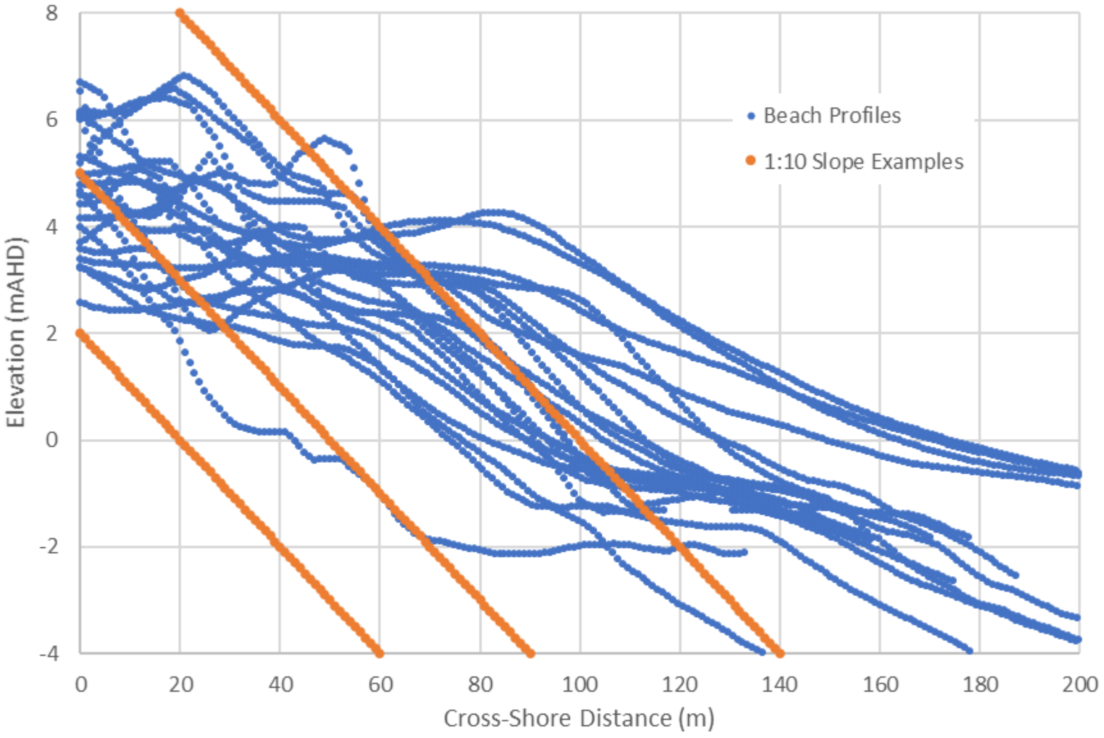

Figure B-2 Kiama Beach Profiles with Example 1:10 Slopes

L_0 is the wave length which is related to the wave period T based on linear wave theory as follows:

$$L_0 = \frac{gT^2}{2\pi}$$

For this study with random wave conditions, H_0 has been taken as the deep-water significant wave height at the Port Kembla wave buoy (~80m depth), with T taken as an appropriate peak wave period for that condition (note higher period is more conservative for setup/runup conditions). For inundation hazard assessments, the waves that are most likely to coincide with high-tide conditions are likely to be of greatest interest. As such the 6-hourly wave conditions have been used at the same recurrence interval (ARI) as the storm tide (i.e. 100-year storm-tide combined with a 100-year wave height to calculate the wave runup level). The 100-year wave condition is not likely to be perfectly correlated with a 100-year storm-tide, however it is a conservative assumption and one that is commonly made.

The wave runup conditions that have been applied over the Kiama coastline are shown in Table B-3.

Table B-3 Wave Runup Conditions

Inundation Event Frequency	Offshore Wave Height (m)	Offshore Wave Period (s)	Wave Runup Height (m)
HAT	N/A	N/A	0.0
20-year ARI	6.9	12.5	3.79
100-year ARI	7.9	12.5	4.06

B.7 Combined Future Inundation Modelling

In order to calculate appropriate inundation levels to assess for future planning timeframes, the various components of potential future inundation need to be combined. As each component is uncertain, a probabilistic approach has been used to incorporate the statistical distributions and derive a range of outputs based on certain likelihoods.

For each future timeframe (i.e. 2020, 2040, 2070, 2120), three different scenarios have been assessed:

(1) For **Tidal Inundation**: HAT, the highest astronomic tide, combining tidal effects and SLR. Areas inundated by the condition can be considered to be inter-tidal and therefore effectively permanently inundated. Note that no wave runup is added to HAT inundation levels as these levels can occur without any wind or wave activity.

(2) For **Coastal Inundation** (20-year); This represents conditions that can be reasonably expected to be experienced within a lifetime, but it takes a large and rare event to do so. Statistically, these occur once on average in 20 years over a long period. However, they may occur multiple times in short-succession and then not for a long time. There is a ~62% chance of them occurring in any given 20-year period.

(3) For **Coastal Inundation** (100-year), this represents conditions that occur quite rarely. Inundation levels higher than this become substantially rarer and less certain. These conditions are often used to represent very high magnitude conditions for planning purposes. There is approximately a 1% chance of them occurring in any year.

Each of these scenarios has been calculated by combining the probability distributions of the storm-tide and the SLR. As described in sections B.4 and B.5, both of these can be described as normal distributions centred around a mean that is commonly reported as the given value. In order to probabilistically assess inundation extremes, these distributions can be added by an integral convolution of the normal distributions. The result is also a normal distribution with a mean and variance given as the sums of the means and variances of the input distributions. This relies on the assumption that there is no correlation between the SLR and storm tide distributions. While in reality there will be a small component of correlation due to the effects of existing SLR in the water level record, and/or any non-linear interactions of water levels as they approach the shore, these effects are small (millimetres to centimetres) relative to the overall mean water level increases (meters). The use of the integral convolution negates the need for a stochastic sampling approach (so called ‘monte carlo’ simulation) and allows for exact percentiles to be extracted from the final distribution.

The HAT levels have been assumed to have a variance of zero (i.e. a constant distribution) when combined with SLR. Additionally, HAT levels have not been calculated with an additional increase due to wave runup as they are intended to represent a permanently inundated, inter-tidal area.

Constant wave setup/runup values have been applied as additional offsets to the probabilistic still-water inundation levels. These have only been added in an area of ‘wave influence’ within 100m of the shoreline as described in Section B.6.