Flooding Tailwater Levels for NSW Coastal Entrances

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Ocean water levels often differ from expected tidal predictions. Such differences, referred to as tidal residual, are caused by a range of meteorological and oceanographic conditions. Tide and tidal residuals can influence the level of flood risk in tidal waterways.

This study examined 88 water level records from a network of coastal NSW gauges. Some sites have collected data since the 1980's and the average record length of all sites is just under 20 years. A full range of NSW coastal environments was considered from the open ocean to small creeks. A range of techniques were used to examine contributions of key metocean drivers to water level variation, including; tide, storm surge, wave setup and coastal trapped waves. Additional data sets, such as; 20 coastal weather stations; 20 streamflow gauges and 7 offshore waver rider buoys were examine in regard to driving influences on coastal water levels.

Tidal and residual water levels are independent for open ocean locations but not for locations within tidal waterways. Gauges located just inside river entrances deviate significantly and systematically from true ocean levels. While in the past this difference was attributed to wave setup, the findings of this investigation support the current understanding that only very shallow entrances (< 2 m) are susceptible to significant wave setup.

This study presents methods to calculate dynamic tailwater levels based on true open ocean locations for use as tailwater conditions of coastal flood models and design curves that can be used to estimate extreme residual return interval values. These combined can be used to determine dynamic tailwater levels for NSW tidal waterways.

Investigations of metocean drivers presented in this study provide an explanation for much of the variability in non-tidal water level variations. However, some variation and the physical processes responsible remains unclear and poorly understood.

INTRODUCTION

Along the NSW coastline, the most extreme water level residuals occur during storm surge conditions when the strong winds and low atmospheric pressures of intense coastal storms 'pile-up' water along the coast. While significant attention is given to these storm surge events, this study examines the contributions of a full range of driving mechanisms, in an effort to build a complete picture of tidal residuals, their causes and their variation along the NSW coastline.

This paper presents a summary of Stage 1 of the two stage study program. Stage 1 was completed through a joint collaboration between SMEC and University of

Queensland (UQ). The study program is funded by the Natural Disaster Resilience Program (NDRP)[1] and administered by NSW Office of Environment and Heritage.

The overall study program objective is a better understanding of water level processes within NSW's tidal waterways and the application of this knowledge to flood risk assessments in the coastal zone. The specific objectives for Stage 1 of the study were:

- Investigate the combined effects of ocean tides, storm surge, wave setup, wave overtopping and other possible contributors on dynamic tailwater level conditions at different types of NSW coastal entrances.
- Develop simple methods to calculate dynamic tailwater levels at the coastal entrances.
- Provide design curves for extreme entrance water levels under coastal flooding (excluding and including catchment flooding) conditions.

BACKGROUND INFORMATION

The study area covers the NSW coastline and gauged tidal waterways (Figure 1). Located in the temperate mid-latitudes, between -28.8° to -37.5°, the NSW eastern coastline boarders the Tasman Sea part of the southern Pacific Ocean. Major floods are predominately associated with east coast maritime lows and in the northern regions, tropical cyclones (Speer et al, 2009).

Water level variations along the NSW coastline are driven by processes include: astronomical tides, storm surge, wave setup, wave run-up, wave overwash, coastal trapped waves, ocean circulation, climate oscillations, tectonic processes and sea level rise (MHL, 2011).

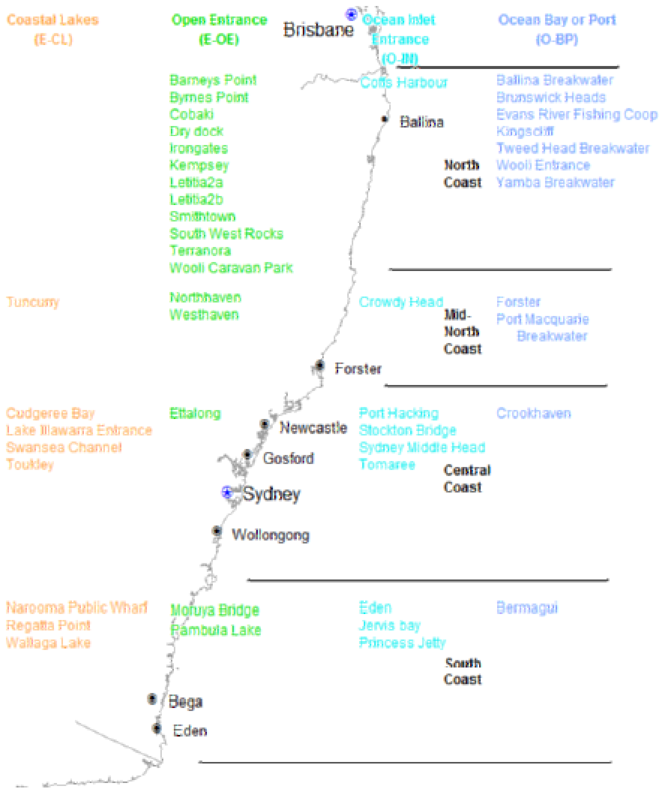

Figure 1: The study area covers the NSW Coastline

[1]The Natural Disaster Resilience Program (NDRP) is a disaster mitigation and community resilience grant program and is funded through shared contributions of the Australian Government and state governments.

DATA AND ANALYSIS

Water Level Data

The Manly Hydraulics Laboratory (MHL) operates a network of water level gauges covering the fluvial basins and nearshore regions of coastal NSW. Progressively established since 1980, there are currently about 200 continuous collection sites. The network is operated by MHL on behalf of OEH. This gauge data forms the primary basis for this study.

88 water level gauges that have been selected for use in this study. The average record length is 19.6 years, with some sites ranging up to 30 years. Sites with records covering less than 9 years have generally been excluded. Overall data capture rates range from 43% to 99.5%, with most sites achieving coverage greater than 85%. The sampling interval for most gauges is 15-minutes. Offshore sites are sampled at hourly intervals (MHL, 2011).

In an effort to present the information in a manner that allows for comparison of sites, water levels are presented relative to Australian Height Datum (AHD). About a third of the sites, generally being ones with more ocean influence, were provided relative to local datum. At present there is no standard documentation available to covert between local datum and AHD (MHL, 2011). However, MHL provided unofficial offsets that have been used in this study.

Site Classification

Each gauge site was classified on the basis of geographic location, ocean exposure and estuary type, where ever a gauge was located within an estuary. Table 1 provides a qualitative summary of the distribution of each gauge type. Geographical classification follows the four storm regions defined in PWD (1985) including the north coast, mid-north coast, central coast and south coast.

The selected gauges cover the full range of coastal and estuarine conditions that occur along the NSW coastline. Distinction is between ‘ocean’ (given an ‘O’ prefix) and ‘estuarine’ (given an ‘E’ prefix) gauges sites was based on ocean exposure. Ocean gauges were further divided into three types roughly following the system proposed by MHL (2011). These types are:

- Ocean Offshore (O-OFF) gauges are located between 250 m and 3.5 km offshore, at depth of approximately 30 m.

- Ocean Bay or Port (O-BP). These are sites with relatively small fluvial influence. They include non-riverine locations on the ‘open’ coastline, such as Coffs Harbour and Crowdy Head. They also include sites within large open bays or ports with comparatively small fluvial influence (such as Port Jackson, Port Stephens and Jervis Bay). Stockton Bridge is an exception, in that it is located 6 km upstream on a river entrance (Hunter River). However, it is near the Hunter Port area where a deep (>15 m LAT) channel is maintained, reducing frictional losses between the ocean.

- Ocean Inshore (O-IN). These gauges are generally located within 1 km of stable ocean entrance, such as on the breakwaters of a trained river entrance (e.g. Tweed River Breakwater).

The estuarine classification follows that set out in the Appendix of the *NSW Government Flood Risk Management Guide* (NSW Government, 2011). The four estuarine types are:

- Coastal Lakes (E-CL). Large coastal lakes (e.g. Lake Macquarie, Lake Illawarra) are treated separately. Although these systems often having similar inlet structures to open entrances, the large hydraulic mass alters the tidal and flooding behaviour of the systems.
- Open Entrance (E-OE). These are tidal waterways that have permanent open inlets. This type includes the trained river entrances (Richmond River, Tweed River) but also entrances that are otherwise stable (Pambula Lake).
- Shoaled Entrances (E-SE). These waterways inlets have varying degrees of shoaling which varies depending on the topography of the inlet and the dominant coastal processes. All have some degree of choking of the tide.
- Intermittently Closed and Open Entrances (E-IOC). These waterways are not always tidal, as the entrances are normally closed or partially blocked. Examples include the coastal lagoons (or ICOLL's) of the central region, (e.g. Avoca, Manly) and small coastal creeks (e.g., Killick Creek at Crescent Head).

Table 1 – Summary of water level gauge classification

Classification		Distribution				*sub-total*
		North	Mid-North	Central	South	
Open (O)	Offshore (OFF)	2	2	0	1	*5*
	Bay or Port (BP)	1	1	4	3	*9*
	Inshore (IN)	7	2	1	1	*11*
Estuarine (E)	Coastal Lake (CL)	0	1	4	3	*8*
	Open Entrance (OE)	12	2	1	2	*17*
	Shoaled Entrance (SE)	5	3	1	5	*14*
	Intermittent Open Closed Entrance (IOC)	5	3	10	6	*24*
	Sub-Total	*32*	*14*	*21*	*21*	*88*

The classification of gauge locations is largely a subjective exercise and depends on the issue in question. There are variations within each of the classes, particular for estuarine sites. Some gauging stations, for example at the more shoaled end of the E-SE class, may arguably be classed as E-IOC.

Other Metocean Data

The interpretation of water level data was aided by correlation to twenty (20) coastal weather stations, twenty (20) coastal streamflow gauges and seven (7) offshore waverider buoys.

Analysis Methods

This study focused on the entire record from a large number of tide gauges. Various techniques were used to examine tidal behaviour and proportion the occurrence of tidal residual according to metocean drivers and other physical interactions. Techniques broadly included:

- Analysis included the decomposition of total water level into tidal and non-tidal (or residual) components.

- Tidal climate of NSW coastline was reviewed with reference to the 88 water level gauges.

- Descriptive statistics and extremes for water level and tidal residual were deriving along the NSW coast.

- A database of historical storms impacting the NSW coastline was compiled to provide a synoptic typing of extreme residual events.

- The likely contribution of wave setup to residual events was examined across geographic locations and entrance types. This was done by isolating conditions were wave processes were likely to be the largest contributor to non-tidal water level variation.

- Coastal trapped waves that have occurred along the NSW coast were identified and their basic properties determined.

KEY RESULTS AND DISCUSSION

Tidal Behaviour

Figure 2 shows the ocean tidal characteristics along the NSW coastline, as described by ocean ('O') tidal planes. Open ocean tides along the NSW coastline are relatively uniform for with a mean tidal range of 1.93 m that increases by about 0.2 m with distance from NSW/Victoria boarder, or more specifically from Eden to Tweed Heads. The MHWS tidal plane is around 11 cm higher at Tweed than Eden and higher high tides are expected in the open ocean off Northern NSW than Southern NSW.

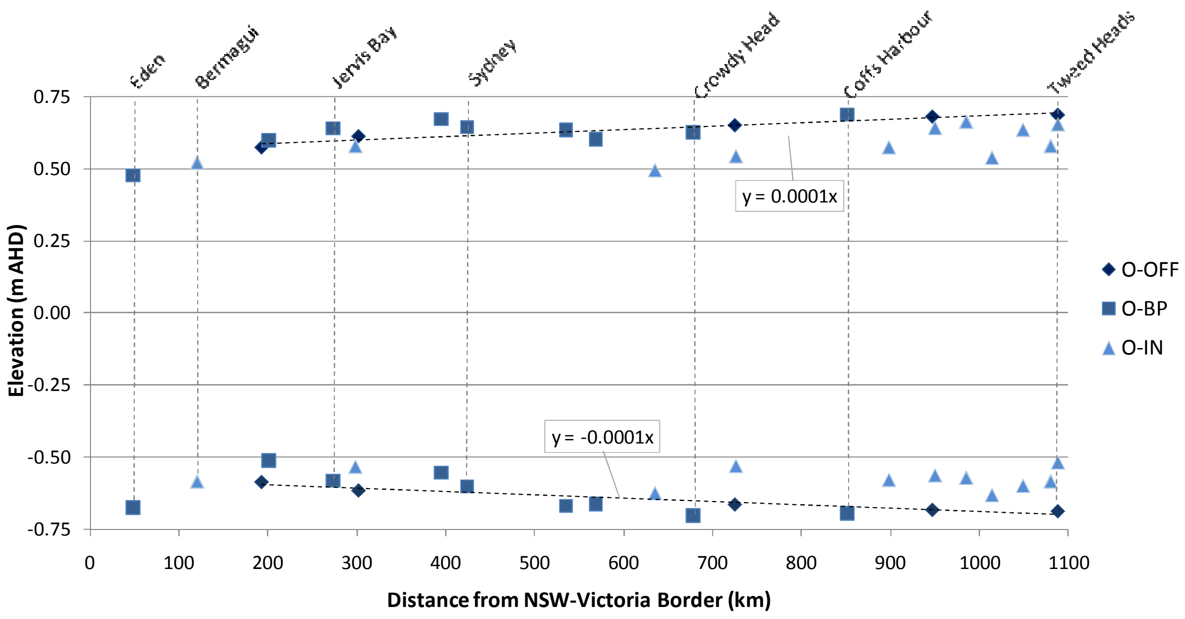

Figure 2 – Variation in ocean tidal planes (MHWS and MLWS) along the NSW coastline

A key physical process occurring within NSW entrances is the loss of tidal amplitude within a short distance from ocean opening. Even for stable and relatively deep entrances (i.e. trained river entrances such as Richmond River) a significant reduction in the tidal range is observed as we move onshore. Just within the entrances, spring high tide can be 0.2 m less than the ocean tide. This is significant when considering that the magnitude of extreme residual events is typically less than 0.8 m. Examples of the significant amplitude decay observed at open entrances are provided in Figure 3. Minor phase shifts also appear to be associated with the magnitude loss and losses are approximately tidal symmetrical, that is equal losses at high and low tide.

The loss of tidal magnitude are due to the hydraulic losses associated with the radial flow patterns associated with the entry of the flood tide and with the ebb jet flows associated with the ebb tide. However, the detailed physics associated with these observations are currently poorly understood and poorly represented in the current set of numerical models used to simulate the hydrodynamics of these inlets. However, the loss of amplitude just inside the ocean entrance has important consequences for flood modelling in that these losses need to be understood and subsequently account for in the models.

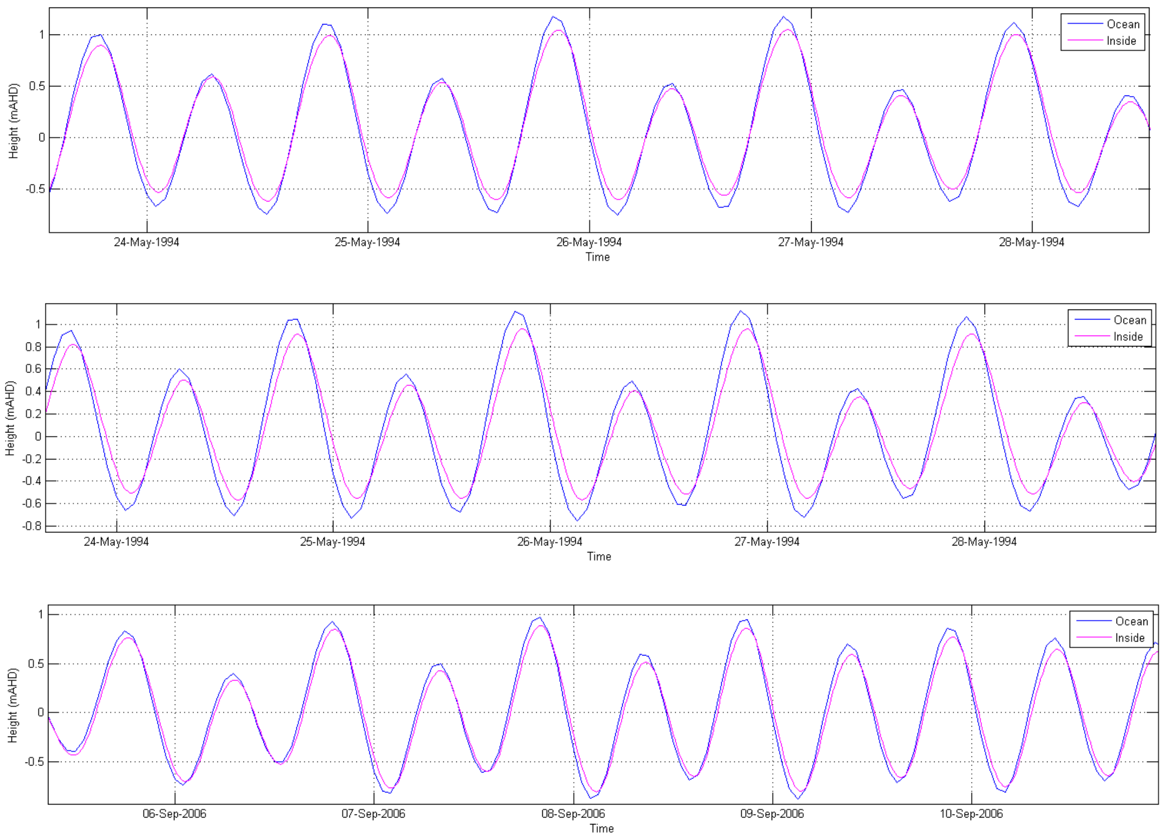

Figure 3 – Examples of reduction in tidal amplitude and slight phase shift typically observed between the ocean and just inside open entrances. Yamba (top), Port Macquarie (middle) and Shoalhaven (bottom) at NSW open entrances

Estuarine tidal characteristics are much more variable and depended on the morphology of the entrance, distance upstream and waterway surface area.

Extreme Events

Figure 4 shows the spatial variations of extreme estimates (at the 100-year recurrence) for all 'O' type gauges. There is a slight increasing trend (approximately 0.2 mm/km) in the 100-year water level exceedance levels from south to north. Extreme water level estimates are approximately 20 cm higher in northern NSW. This is partly attributed to the increase in ocean tidal range and to an increasing trend (north to south) in extreme residuals. While the overall increasing trend in extreme residuals is approximately 0.1 mm/km (south to north) it may not be uniform along the NSW coastline seems to peak around the mid-north coast region.

Table 2 presents 100-year recurrence extreme estimates (and 95% confidence intervals) averaged across gauge type as a further summary of the variation observed across 'O' gauge types. The values indicate that while water level extremes tend to reduce as we move onshore, the reverse is observed for residual extremes.

Table 2 – Type averaged 100-year ARI extreme estimates for all gauges

Type	Water level (mAHD) 90% CI in brackets	Residual (m) 90% CI in brackets	Mean Duration (days)
O-OFF[1]	1.54 (0.03)	0.61 (0.07)	3.8
O-BP	1.42 (0.03)	0.58 (0.04)	3.4
O-IN	1.39 (0.03)	0.81 (0.12)	3.8
E-OE	1.35 (0.03)	1.01 (0.23)	4.7
E-CL (Lake Proper)	1.31 (0.21)	1.36 (0.35)	6.2
E-CL (Entrance Channel)	1.11 (0.07)	0.71 (0.15)	4.8
E-SE	1.70 (0.23)	1.58 (0.24)	4.1
E-IOC	2.23 (0.22)	2.16 (0.28)	4.8

Note: The purpose of the values provided in the above table is comparative only. They should not be used for design estimates or any other purpose.

Locations that are representative of open ocean conditions (gauges classified here as O-OFF and O-BP) have residual that are independent of tidal phase. This logical statement is supported by observed extreme residual peaks occurring at all phases of the tide with no observed bias (or correlation) with tidal phase. However, gauges located just within river entrances (gauges classified here as O-IN) tend to show considerable bias towards residuals events peaking during the ebb tide (42% on average) and low water (34% on average) tidal phases. This indicates that tidal modulation of residual events (whether they be flood discharge or storm surge related) is strongly bias towards events peaking during lower water levels and/or ebbing flows. The implication is that while these entrances can generate very large anomalies, up to 1.6 m have been observed in the measurements, they are most likely to occur at low or ebb tide phase and do not produce design water level conditions.

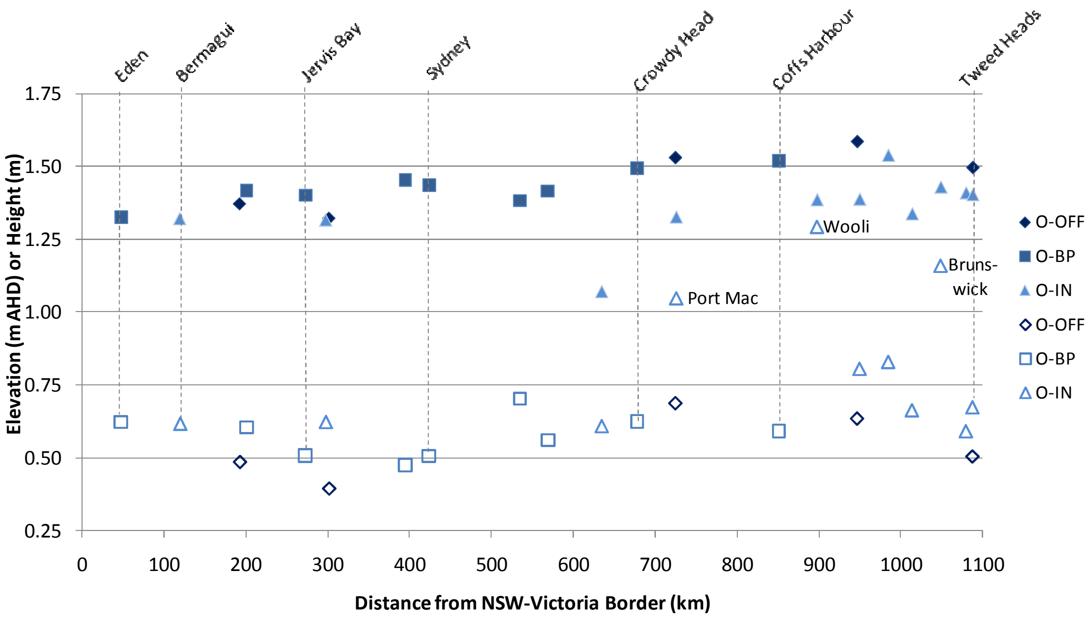

Figure 4 – Extreme (100-year ARI) water level (solid) and residual (outline) by type along NSW coastline

Wave Setup

Using detailed measurements at selected entrances, the team from University of Queensland are currently leading the evidence based research into water level processes occurring at coastal entrances, including investigating wave setup. This study, however, relied on the existing water level gauge network, which is typically limited to only one gauge within the wave effected area of the entrance. In order to provide an overview of the occurrence of wave setup across all gauged entrances, a basic approach was adopted that separated events where large waves occurred in the absences of other metocean drives (i.e. local storms, storm winds and rainfall) from all large waves events (peak wave height over 3 m). The analysis then looked for the relative correlation of wave heights with the peak residual observed.

Figure 5 provides an example of the plots derived, showing event peak residual versus factored offshore significant wave height.

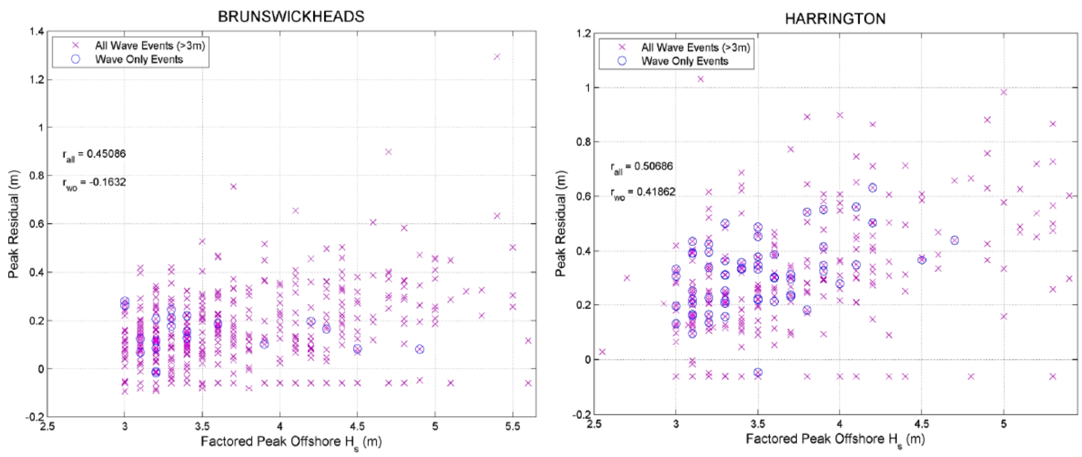

Figure 5 Example plot of peak residual versus factored peak offshore wave height for Brunswick Heads (O-IN) site (left) and Harrington (E-SE) site (right), showing all wave events above 3m and 'wave only events'

Considering *'wave only'* events, ocean sites and sites with deeper and more stable entrance conditions (i.e. O-OFF, O-BP, O-IN, E-OE and E-CL), correlation results (i.e. *'r'* values) show a weak overall correlation between offshore wave heights and peak residual. Examination of the relevant scatter plots also show a general lack of correlation between setup and offshore wave height. O-OFF and O-BP sites are located seaward of breaking and would not be effected by wave breaking or wave setup, so the lack of correlation is expected. However, the weak correlation for O-IN, E-OE and E-CL entrance types indicates a lack of wave setup at most of these 'inside' locations. This is because wave setup is only significant in the ruling depth across the entrance bar is less than 2.5 m, however, most of the trained and larger entrances bars have ruling depths greater than 2.5 m. This is discussed further below.

Stronger correlations between residual and wave height for *'all wave events'* are likely due to large waves associated with weather events that cause elevated coastal water levels (i.e. storm surge conditions) rather than wave setup as a physical driver for these deeper and more stable entrances. This hypothesis is strengthened by the fact that the same general level of correlation for *'all wave events'* was also observed at deep water sites where no wave setup is expected (i.e. O-OFF and O-BP).

The observed *'wave only'* correlation increases slightly for E-SE entrance types with overall stronger positive correlations observed for this entrance type. This is likely attributed to the shallow depths across these more shoaled entrances. Based on the wave setup profiles produced by Nielsen (2010) and Hanslow et al (1996) for shoreline locations and those for river entrances (Tanaka, 2008) wave setup only becomes significant, with increases in water level equivalent to around 5% of offshore wave height, at depths equal to half the offshore significant wave height (H_s). Larger *'wave only'* events on the NSW coast have a peak offshore H_s of under 5 m. This would require depths less than 2.5 m for a potential setup of around 0.25 m. Harrington (Manning River) and Coffs Creek are examples of where the entrance profile lends itself to wave setup. While limiting depths over entrance is a key concern, the shape and exposure of an entrance will also have important implications for wave setup.

For E-IOC entrance types the *'wave only'* correlation is generally weaker indicating a general lack of wave setup. The state of the entrance is likely to be a key factor for these types of sites. Most of these entrances are predominately in closed condition with an entrance berm in place. When these waterways are closed off, wave setup is unlikely to affect water levels during *'wave only'* events as the berm height would generally be sufficiently high. However, some E-IOC entrances may be susceptible to flooding from wave run-up and overwash. Such wave overwash derived flooding is known to have occurred at Lake Conjola in 2006 (Nielsen, 2010).

Overall, findings of the investigations of wave setup completed in this study do not support the notion of wave setup as a key physical driver of water level variations for most of the stable and deeper entrance types on NSW coastline. Our analysis indicates that some shoaled entrances with beach like profiles, such as Coffs Creek, Tuross Head and Harrington, may be susceptible to wave setup. The results of wave setup investigation supports the current understanding of wave setup in river entrance, that only very shallow entrances (< 2 m) are susceptible to significant wave setup. However, significant variability was observed in wave setup correlations across the entrances investigated, the reasons for this variability should be further investigated.

Coastal Trapped Waves

47 CTW events were identified in the water level data between 1989 and 2011, which equates to an average occurrence of just over 2 notable CTW events per year. Of the 47 events, 23 occurred within 5 weeks of another CTW event, indicating that CTW events tend to occur in clusters (similar to East Coast Lows). Over the whole NSW coastline the CTWs travel at speed between 3 and 7.3 m/s, with an average speed of 4.2 m/s. The height of CTW along the coast ranged between 0.1 m and 0.42 m.

Figures 6 provides an example of a coastal trapped wave propagating up the NSW coastline. While the origin of the original disturbance is unknown, given that the disturbance appears in all the Eden records, then it is reasonable to suggest that they are coastal trapped waves originating outside NSW, with their amplitudes generally decreasing as the propagate in a northerly direction. The example given in Figure 6, however, shows a CTW that is magnified as is propagates north, this is likely caused by a re-enforcement of the CTW by strong southerly wind fetches that accompanied this particular CTW.

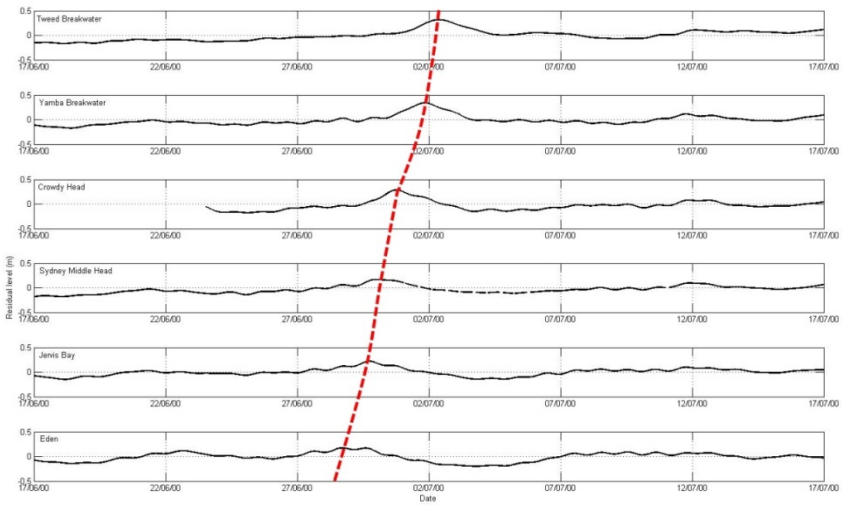

Figure 6 - CTW which appears to grow as it propagates north along the coast.

It has been suggested that the passage of cold fronts across the Bass Strait, also associated strong winds, is a likely mechanism for the generation of CTW that propagate along the NSW coastline (Church et. al., 1986). For all major CTW events identified in this study, strong winds from a predominantly westerly direction occurred in the Bass Strait approximately 1 to 2 days prior to the event. Based on the events assessed the wind conditions at Portland required to generate CTWs are wind speeds in the range of 11 to 16 m/s with peak gusts of 17 to 21 m/s from a south westerly to north westerly direction.

The methods used in this study may not have identified all CTW events and it is possible events occur on a more regular basis.

DESIGN ESTIMATES AND CURVES

For all gauge locations, excluding ocean sites, design curves were produced for extreme residual under flooding (excluding and including catchment flooding conditions). An example of the design curves is provided in Figure 7. These plots included the storm type by the colour of data points. Open circles are used to define where 'low flow' (or no catchment flooding) conditions were observed during an event. Additional design curves can be found in SMEC's report (2013).

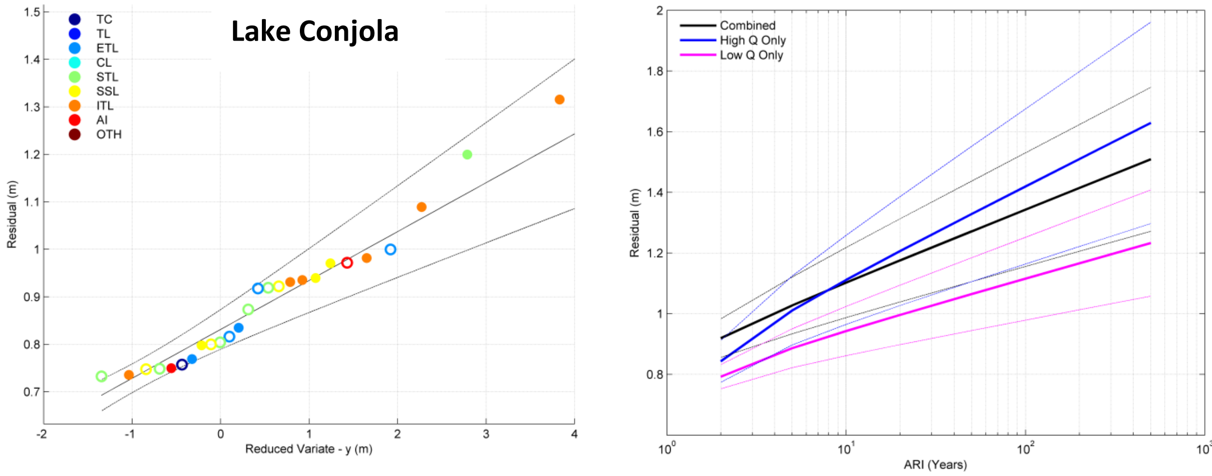

Figure 7 – Example design curve for Lake Cajola – data and fit (left), design curve (right)

RECOMMENDATIONS

Investigations of metocean drivers presented here provides an explanation for much of the variability in non-tidal water level variations, however, some variation and the physical processes responsible remains unclear and poorly understood. Based on the outcomes of this study, recommendations for further investigation are:

- It is clear that water level measured just inside river entrance deviate significantly and systematically from the true ocean levels. The downstream boundary of flood models should be located offshore of the entrance and be prescribed tailwater boundary conditions that are truly representative of ocean conditions rather than the 'ad hoc' use of 'within' entrance conditions.

- The transition from ad hoc inside river tailwater boundary conditions to ocean tailwater boundary conditions should be supported by research to better understand the processes occurring just in the vicinity of river entrances.

- Water level recording should be continued and possible expanded to include more locations. Longer datasets at large number of diverse locations will provide greater value to future studies and coastal risk planning. Particularly, in the context of rising mean sea levels, the extent of existing development and planned future development on the NSW coastline.

- Event-based analysis should be further extended with investigations focusing on very rare and large events which appear to exceed the fitted extreme distributions and the physical reasons (e.g. storm type, track speed, coastal water level conditions prior to the onset of the weather event).

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