ELEVATED WATER LEVELS AT TRAINED RIVER ENTRANCES ON THE EAST COAST OF AUSTRALIA

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The south-east coast of Australia has many low-lying areas at river entrances that are vulnerable to coastal inundation due to high water levels elevated by ocean tides, coastal storms, ocean waves and other drivers. The penetration of elevated entrance water levels into rivers can further intensify river flooding associated with high rainfall events. In this study, historical water level data, which were collected continuously at 17 inshore and 5 offshore permanent tide stations along the East Coast of Australia, are used to study effects of tides and waves on water levels at trained river entrances and also to estimate extreme entrance water levels without major entrance rainfall-related flooding.

Keywords: River entrance; wave setup; elevated water level; storm surge; coastal inundation; extreme water levels

1. INTRODUCTION

Water levels at coastal river entrances are potentially influenced by a variety of coastal drivers including astronomic tides, ocean waves, coastal trapped waves, ocean currents, ENSO and sea level rise. The super elevation of water levels can inundate low-lying coastal areas and place coastal property, infrastructure and human lives at risk. In addition, the penetration of elevated water levels into a river may intensify river flooding associated with high rainfall events through elevation of river entrance tail water conditions. Thus, the study of the effects of tides and waves and the accurate prediction of extreme water levels is of significant engineering, economical, ecological and social importance.

Several studies have been undertaken to examine the effect of wave setup on mean water levels at coastal river entrances. Hanslow and Nielsen (1992) applied a manometer, which was developed by Nielsen (1988), to simultaneously measure mean water levels at a trained river entrance of the Brunswick River and on its neighbouring sandy beach. A large wave setup was measured on the beach, but very small at the trained river entrance. Hanslow et al (1996) concluded that the absence of wave setup at the trained entrance of the Brunswick River was due to the momentum flux of the river flow and its influence on the incoming waves. This may not be the case when rising tides propagate with ocean waves in the same direction. Dunn (2001) attempted to further explain the field data of Hanslow et al (1992, 1996) by applying different analytical and numerical models. He then concluded that two of the main reasons for small and sometimes immeasurable wave setup height in the Brunswick River entrance were wave energy dissipation due to bottom friction and wave energy loss due to wave rolling on the training breakwaters. Finally, Dunn (2001) postulated that if ocean waves broke at the trained river entrance without any wave energy dissipation due to bottom friction and side training walls effects, the wave setup at the trained river entrance could be significantly high. However, the bottom friction may not be a key factor responsible for little wave setup at the trained river entrance because such the bottom friction does also exist at untrained river entrances where large wave setup heights were found. Tanaka and Shuto (1992) also directly measured mean water levels at two river entrances, the Nanakita River without trained walls and the Natori River with trained walls. At the Nanakita River entrance, a maximum wave setup of 66cm was measured and the wave setup height was about 10~20% of the deepwater wave height but generally smaller than those measured on natural beaches. In contrast, little wave setup was found at the Natori River entrance with training walls. Tanaka et al (2000) also undertook a field study of wave setup at another untrained river entrance of the Natsui River. They also found that wave setup heights at the Natsuit River entrance were similar to those at the Nanakita River entrance. Recently, Lee and Tanaka (2006) measured wave setup heights at an untrained river entrance of the Shiribetsu River and had drawn similar conclusions on wave setup to those of Tanaka and Shuto (1992) and Tananka (2000).

In this study, a number of long-term field datasets on mean water levels collected at coastal entrances of rivers and large bays and harbours along the Australian East Coast of New South Wales (NSW) will be used to investigate the effects of tides and wave setup on mean water levels measured and estimate *n*-year return extreme water levels at the NSW coastal river entrances.

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2. FIELD SITES AND INSTRUMENTATION

2.1 Australian East Coast

The Australian East Coast of NSW is subject to a moderate wave climate predominantly from the south to south-east. Previous studies have found that the average deepwater significant wave height is about 1.6 m and the average peak period about 9.7sec. The NSW wave climate is found to be periodically affected by large coastal storm systems and the coastal storms vary spatially and temporally with storm genesis, intensity and track. The distribution of peak storm wave heights varies along the coast with 100-year return wave heights of around 9.0m off the coast of Sydney, but with smaller extremes both to the north and south (You and Lord, 2008; Shand et al, 2011). Ocean tides on the NSW coast are semi-diurnal. The tidal range is about 1m during neaps and about 2m during springs and increases slightly from the south to the north of the coast by about 20cm (MHL, 2009).

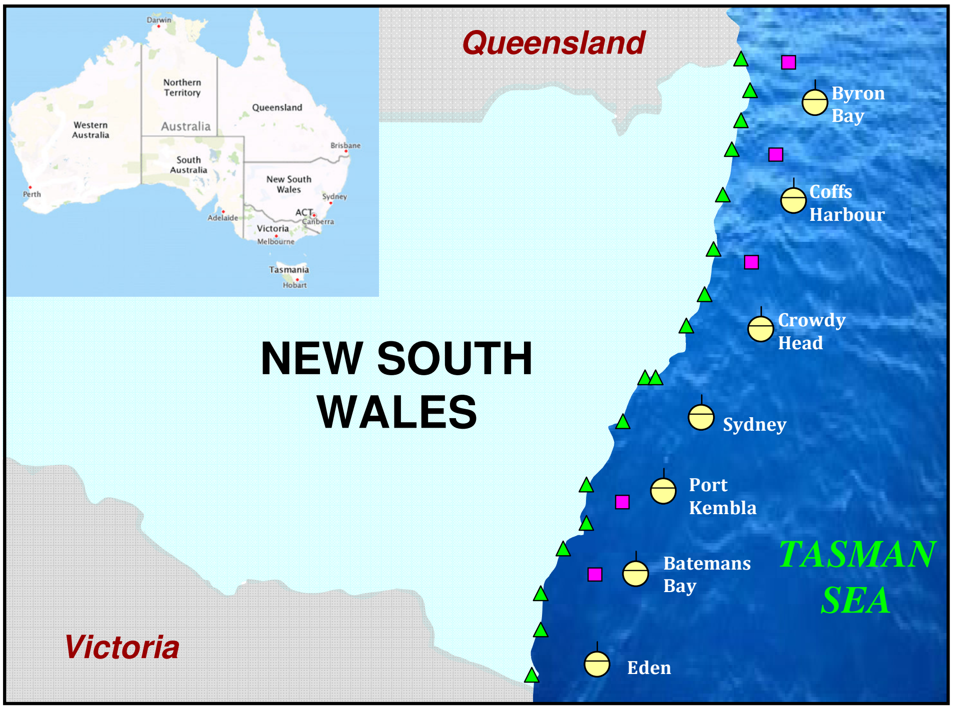

Figure 1: Study sites-- Historical water level data collected at 17 inshore (Δ) and 5 offshore (□) permanent tide stations and wave data at 7 wave stations along the Australian East Coast of NSW in Tasman Sea.

2.2 Field Sites

There are 17 inshore and 5 offshore permanent tide stations as well as 7 wave rider buoys deployed along the Australian East Coast of NSW to collect long-term water level and wave data at the NSW coastal entrances of rivers and large bays (see Figure 2). Three types of tide gauges were mounted at breakwaters, jetties, wharfs and inside bays and harbors in shallow waters at the 17 inshore stations. The 5 offshore pressure transducers were installed on heavy steel tripods sitting on the seabed in water depths of 22~28m. Figure 2 shows some of the inshore and offshore sites. The water level data collected inside the large bays are used to determine how astronomic tides decay when the tides propagate into the bays from the offshore stations. The water level data collected at the offshore stations are expected to be less affected by the nearshore processes such as wave setup and rainfalls/runoff than those at the inshore stations. The long-term water level dataset, which were collected at Fort Denison inside Sydney Harbour under minor influence of ocean waves, are used to examine the combined effects of ocean waves and tides on mean water levels at the entrances of the rivers and bays. The Fort Denison data were collected with analogue tide gauges before 1996 and digital tide gauges after 1996.

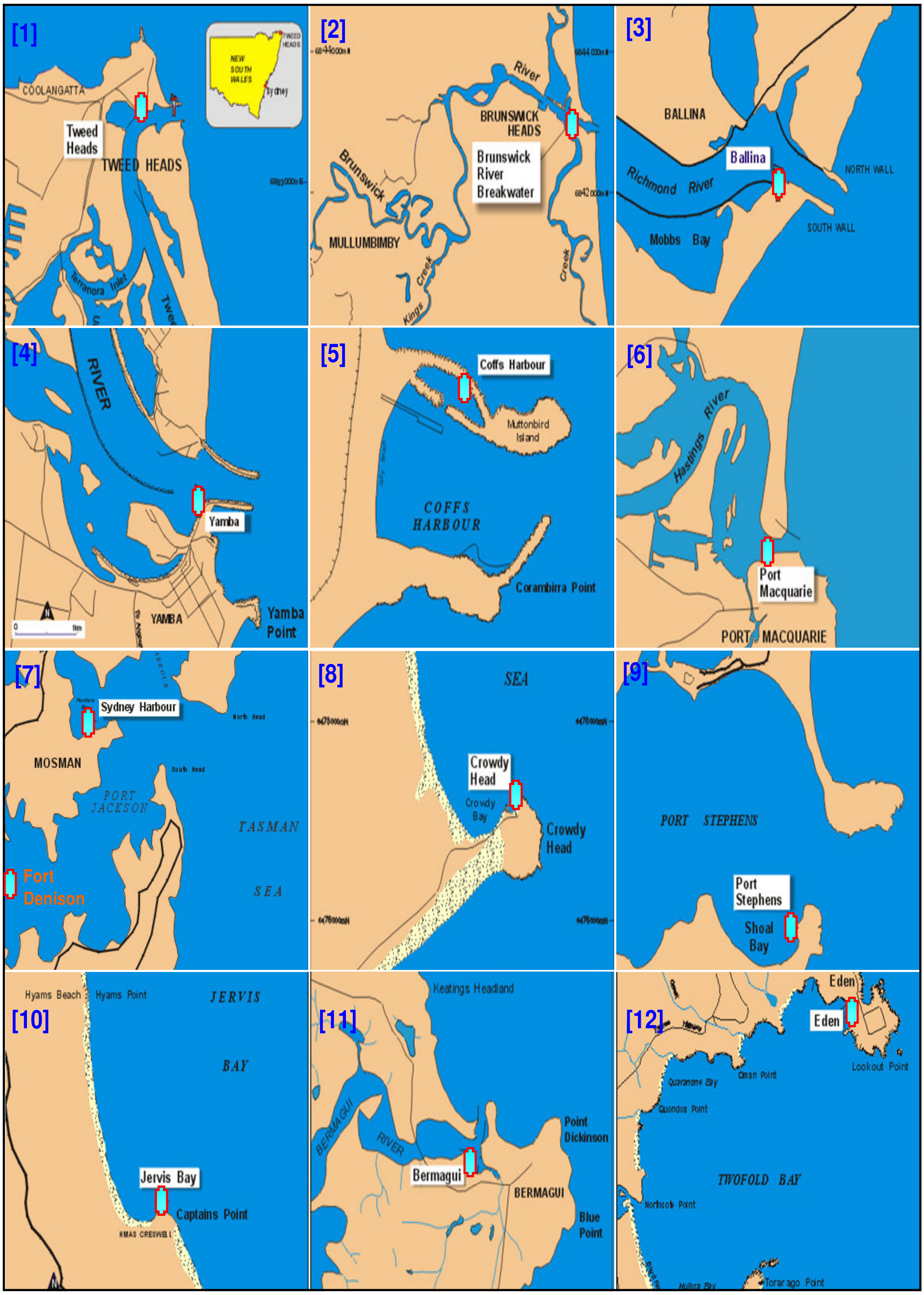

Figure 2: Location maps of the 12 inshore tide gauges deployed at the river entrances [1, 2, 3, 4, 6, 11] and inside the bays [8, 9, 10, 12] and harbors [5, 7] along the Australian East Coast of NSW. Note the upward/downward direction of the location maps is the north/south.

2.3 Instrumentation

Three types of instruments were used to collect the water level data at the 22 inshore and offshore permanent tide stations along the NSW coast, namely, electromagnetic tide gauges (EG), pressure transducers (PT) and float-well tide gauges (FW). The pressure transducers were applied to collect the offshore data only, while both the EG and FW gauges recorded the inshore data.

The FW gauges recorded the water level data at a 0.1Hz sampling rate for 160 seconds every 15 minutes. The water level is sensed by a float connected to an optical shaft encoder which is recorded every 10 seconds for 160 seconds, averaged and then stored every 15 minutes. The data were stored by a solid state recorder which has a capacity of retaining up to six months of data. The data were transferred wirelessly to the Manly Hydraulics Laboratory (MHL) at the end of each field deployment or physically downloaded in the field. The water level data at 4 of the 17 inshore stations were collected by the FW gauges. Table-1 briefly summarized instrument type, stating date, entrance type and sampling techniques adopted for the FW gauges. The EG gauges collected the water levels at a 1Hz or 2Hz sampling rate for 1min or 15min every 15min. The gauges recorded the averaged water levels every 15min continuously. The water level data were downloaded every 24~48 hours and transferred via radio to a shore station that is linked to the MHL computer centre with a telephone modem or directly from the pole via cellular phone. The water level data at 13 of the 17 inshore stations were collected by the EG gauges. The PT gauges recorded 40-second averaged water levels every hour. The data were stored internally in the PTs and downloaded to the computer by the data retrieving divers after the PTs were deployed for a period of 5~8 months at the offshore sites.

Table-1. Summary of site name, starting date, entrance type, gauge location and type, instrumentation and datum for the inshore and offshore stations deployed along the NSW coast, where PT=Pressure Transducer FW=Float Well and EG=Electromagnetic Gauge. Note the EG was used at Fort Denison from 1996.

Location Name	Starting Date	Entrance Type	Gauge Location	Gauge Type	Sampling Rate (Hz)	Interval (min)	Local Datum
Tweed Heads	1987	River Entrance	0.6 km inshore of river entrance	EG	2Hz	15	Tweed River Hydro Datum
Tweed Offshore	1982	Offshore	3.5km offshore h=28m	PT	Integrated	60	Local mean sea level
Brunswick HD	1988	River Entrance	0.6 km inshore of river entrance	FW	0.1Hz	15	Brunswick River Flood Mitigation Datum
Ballina	1986	River Entrance	0.7 km inshore of river entrance	EG	1Hz	15	Low Water Ordinary Spring
Yamba	1986	River Entrance	0.9 km inshore of river entrance	EG	1Hz	15	Port Datum
Yamba Offshore	1987	Offshore	1.9km offshore h=23m	PT	Integrated	60	Local mean sea level
Coffs Harbour	1987	Harbour	Inside boat harbour	EG	2Hz	15	Coffs Port Datum
Port Macquarie	1986	River Entrance	0.5 km inshore of river entrance	FW	0.1Hz	15	Australia Height Datum (AHD)
Macquarie Off	1984	Offshore	1.4km offshore h=22m	PT	Integrated	60	Local mean sea level (MSL)
Crowdy Head	1986	Harbour	Inside boat harbour	EG	2Hz	15	Crowdy Head Datum
Forster	1986	River Entrance	Breakwater	EG	1Hz	15	Forster Hydro Datum
Port Stephens	1985	Bay	0.7km from bay entrance	FW	0.1Hz	15	Port Stephens Hydro Datum
Middle Head	1987	Bay	Middle Head 3km from harbour entrance	EG	1Hz	15	Indian Spring Low Water
Fort Denison	1914	Bay	6km from entrance	EG	0.5Hz	6	Indian Spring Low Water
Port Hacking	1988	Bay	2km from entrance	EG	2Hz	15	Indian Spring Low Water
Shoalhaven Off	2005	Offshore	2km offshore h=25m	PT	Integrated	60	Local MSL
Crookhaven	1991	River Entrance	0.8km inshore of river entrance	EG	1Hz	15	AHD
Jervis Bay	1989	Bay	7km from Bay entrance	EG	1Hz	15	Chart Datum
Ulladulla	2007	Harbour	Inside boat harbour	EG	1Hz	15	AHD
Batemans Off	2000	Offshore	250m offshore h=28m	PT	Integrated	60	Local MSL
Bermagui	1987	River Entrance	0.4km inside river entrance	FW	0.1Hz	15	Bermagui Local Hydro
Eden	1986	Harbour	Inside boat harbour	EG	2Hz	15	Twofold bay Hydro Datum

2.4 Station Datum

The water level data were recorded at the inshore stations with different locally established datums (see Table-1), and thus they can't be compared directly. In order to make a direct comparison of the inshore water level data collected at different sites, all locally established datums are converted to the local Mean Sea Level datum (MSL) under the assumption that the local MSL datum may not significantly vary spatially from station to station on the NSW coast. The local MSL datum is determined by summing all water level data collected at a station and then dividing the summation by the total number of data points to obtain the mean water level relative to the locally established datum and finally subtracting the mean water level from individual water level data point to obtain the water level data relative to the MSL. The use of the MSL datum for both the inshore and offshore stations will enable us to compare the inshore and offshore data directly.

There was no absolute local datum established for the offshore tide stations. Thus, only the local MSL, which was averaged over the length of individual field deployment of up to 5~8 months, was adopted for the offshore stations. The local MSL is expected to vary slightly from station to station, depending on the record length of individual field deployment and also on the meteorological, oceanographic and climate conditions. This method potentially removes inter-annual and longer term variability that was found from the long-term sea level record at Fort Denison (You et al, 2009). At this stage, the use of the MSL datum is only the way to make a direct comparison of the inshore and offshore data unless the permanent datum has been established for the offshore stations. Caution should also be taken in the comparison with neighboring long term continuous data sets.

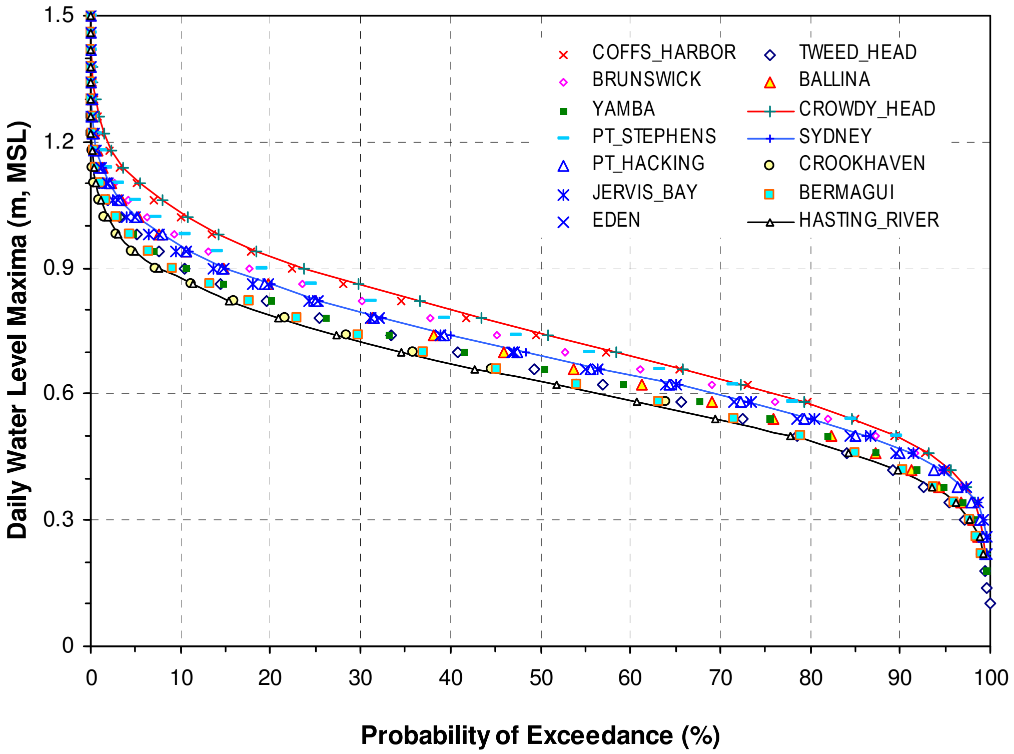

Figure 3: Distributions of daily water level maxima computed from the 14 inshore stations. The daily water level maxima at the stations (Crowdy Head and Eden) directly exposed to ocean waves are generally larger (~5cm) than those inside the bays or harbors (Sydney, Pt Stephens, Port Hacking, Jervis Bay), and about twice larger (~10cm) than those at the trained river entrances, excluding the Brunswick River entrance.

3 Distribution of Daily Water Level Maxima

The historical time-series field data from each of the inshore stations are analyzed to generate the large sample of daily water level maxima. The probability of exceedance for a given daily maximum water level H, Q(H), is then calculated to be $Q(H)=n/m$, where n is the number of daily maxima larger than H, and m is the total number of daily maxima collected at a station. The distributions of H, which are calculated from the 14 inshore stations, are shown in Figure 3, where the red and black lines are the upper and lower limits of daily water level maxima at the inshore stations. The data from the site of Shoalhaven is not included in Figure 3 as its entrance is generally closed. It can be seen that the daily water level maxima at the north coast harbour sites (Coffs Harbour, Crowdy Head) are largest, generally larger (~5cm) than those at the central to south coast (Port Stephens, Sydney, Port Hacking, Jervis Bay and Eden), and much larger (~10cm) than those at the south coast river entrance sites excluding the Brunswick River entrance site. Little wave setup is expected at the bay sites as these locations are generally well protected from the dominant wave direction and wave breaking may also be negligible.

The daily water level maxima at the trained river entrances are generally lower than those inside the bays or nearby the stations directly open to the coast. The lower daily water level maxima at the trained river entrance is likely to be due to tidal energy loss when tides propagate thorough the river entrance to the inshore station that is generally located some distance inside the entrance (see Table-1). The difference of a few centimetres in the daily water level maxima at the river entrances in Figure 3 may be due to the fact that the tide gauges were located at different distances from the open coast.

4 Empirical Distribution of Extreme Water Levels

In order to examine the effects of waves, tides and the other contributors to extreme water levels (e.g. water levels exceeding 1.0m) at the inshore and offshore stations, the empirical distributions of extreme water levels measured at the stations are examined. With the Peaks-Over-Threshold method (POT), the extreme water level data on monthly maximum water levels, which are also required to exceed a threshold value of 1m, are extracted from the historical time-series water level record at each of the stations to calculate the empirical distribution. The 1m threshold level is taken to be approximately equal to the tide amplitude of spring tides on the NSW coast to make sure the statistical independence of monthly water level maxima generated. At the river entrance sites, a few data on extreme water levels, which were associated with rainfall-related river flooding, were removed from the data set according to the rainfall data. The effect of rainfall/runoff on extreme entrance water levels is not investigated in this study. The empirical distribution of extreme water levels is then estimated as

$$Q = \frac{n}{m}, \tag{1}$$

where n is the n^{th} highest water level of monthly water level maxima ranked in descending order, and m is the total number of monthly water level maxima collected at a station. It was discussed by You (2012) that the plotting position formula Eq.(1) is consistent with the definition of the return period

$$T_R = \frac{1}{Q\lambda} = \frac{m}{n} \times \frac{T}{m} = \frac{T}{n}, \tag{2}$$

where $\lambda = m/T$ and T is the record length. With Eq.(2), the return water level data (T_R, H) are generated from the ranked monthly water level maxima at each of the stations, where H is the return water level with a return period of T_R.

In Figure 4, the empirical distributions of the extreme water levels measured at the bay and harbour sites along the NSW coast are compared, where the FT-1 distribution is fitted to the Fort Denison data with the method described in the next section. As depicted in Figure 2, the presence of ocean waves at Fort Denison is minor and can be neglected. Thus, the effect of waves on mean water levels at the inshore and offshore stations can be determined directly by comparing the water level data at Fort Denison to those at the other stations, respectively. It can be seen from Figure 4 that for the bay and harbour sites, the extreme water levels vary along the coast and in general tend to be slightly higher on the north coast than on the south coast although there is some variation between the sites and the north to south trend is not always consistent. The highest water levels are measured at Crowdy Head and Coffs Harbour which stand apart from the locations further south of the coast (see Figure 2). The lowest water levels are observed at Jervis Bay. The data at Eden seems to follow a slightly steeper curve than from other sites. The overall variation is around 10~15 cm.

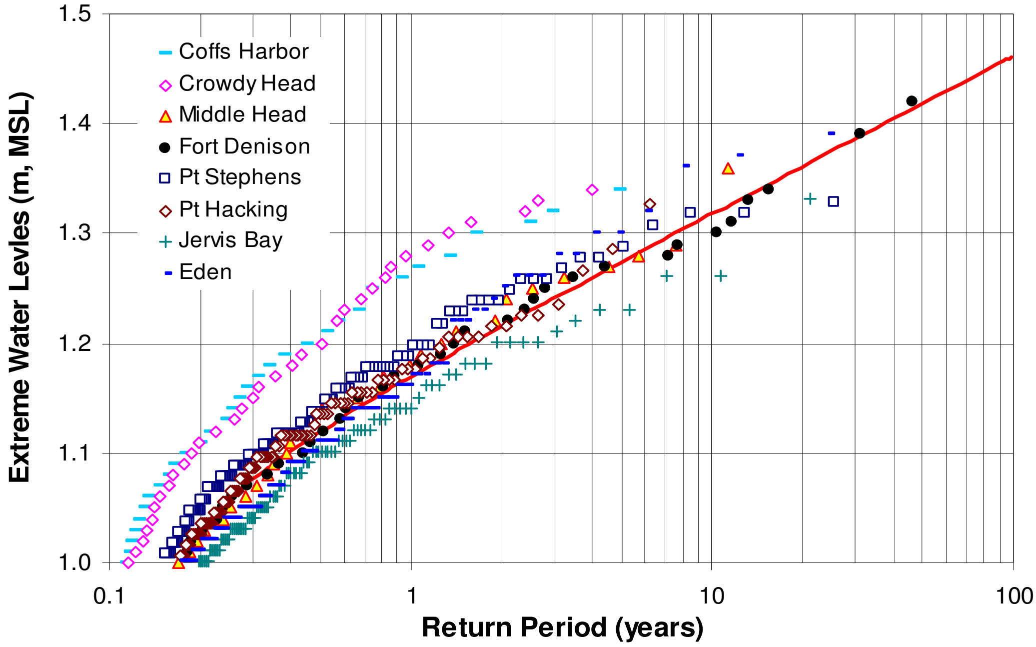

Figure 4: Empirical distributions of extreme water levels measured at the bay and harbour sites along the NSW coast, where the red curve is the FT-I distribution fitted to the Fort Denison data.

In Figure 5, the empirical distributions of extreme water levels measured at different river entrance sites along the NSW coast are also compared. The Fort Denson data, which is fitted to the FT-1, are also included for reference. For the river entrance sites, a similar tend is seen with higher levels on the north coast than on the south coast. The highest water levels were measured at the Brunswick River Gauge and the lowest at the Crookhaven River entrance. For the bay sites, there is some variation between the sites and the north to south trend is not always consistent. The overall variation is around 10 cm. The river entrance data tends to be lower than the bay and harbour data, suggesting the tidal attenuation may be significant at these river gauges.

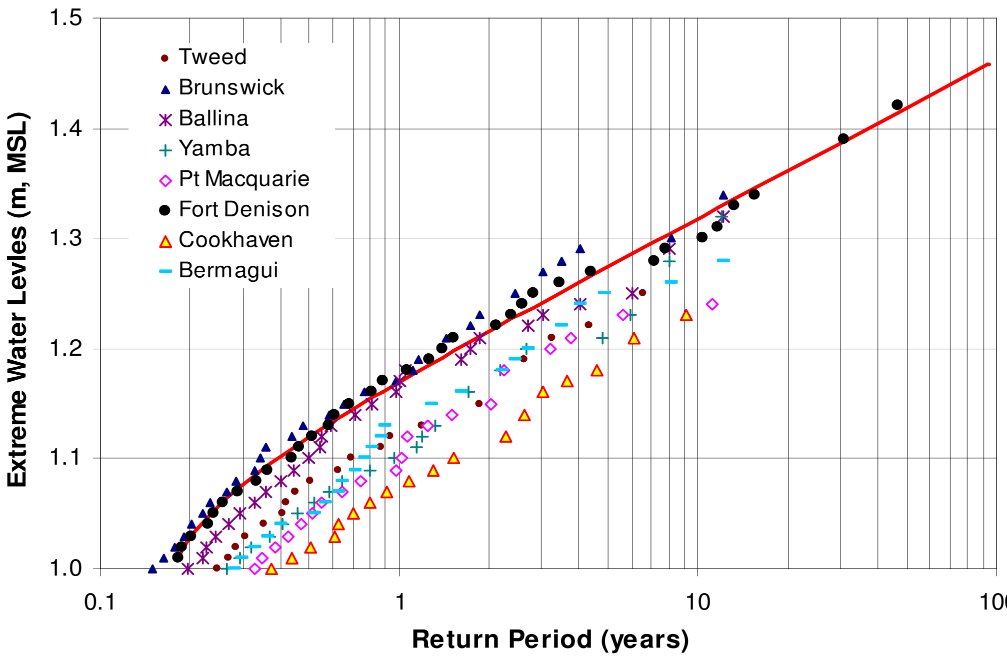

Figure 5: Empirical distributions of extreme water levels measured at the River Entrance sites along the NSW coast, where the red curve is the FT-I distribution fitted to the Fort Denison data.

To further examine water level differences between the offshore and river entrance gauges, the empirical distributions of extreme water levels measured at the offshore sites at the water depths of 22~28m are compared in Figure 6. These plots show that the extreme water levels measured at these river entrances are consistently less than those measured offshore, suggesting significant tidal attenuation between the offshore and river entrance sites. The FT-I is fitted to both the inshore and offshore data. In Figure 6, the two highest water levels at the offshore stations may be underestimated. The use of the local MSL potentially removes inter-annual and longer term variability from individual segment of water level data collected without a locally established datum. Note the use of the MSL datum for the inshore stations with locally established datums will not cause this problem.

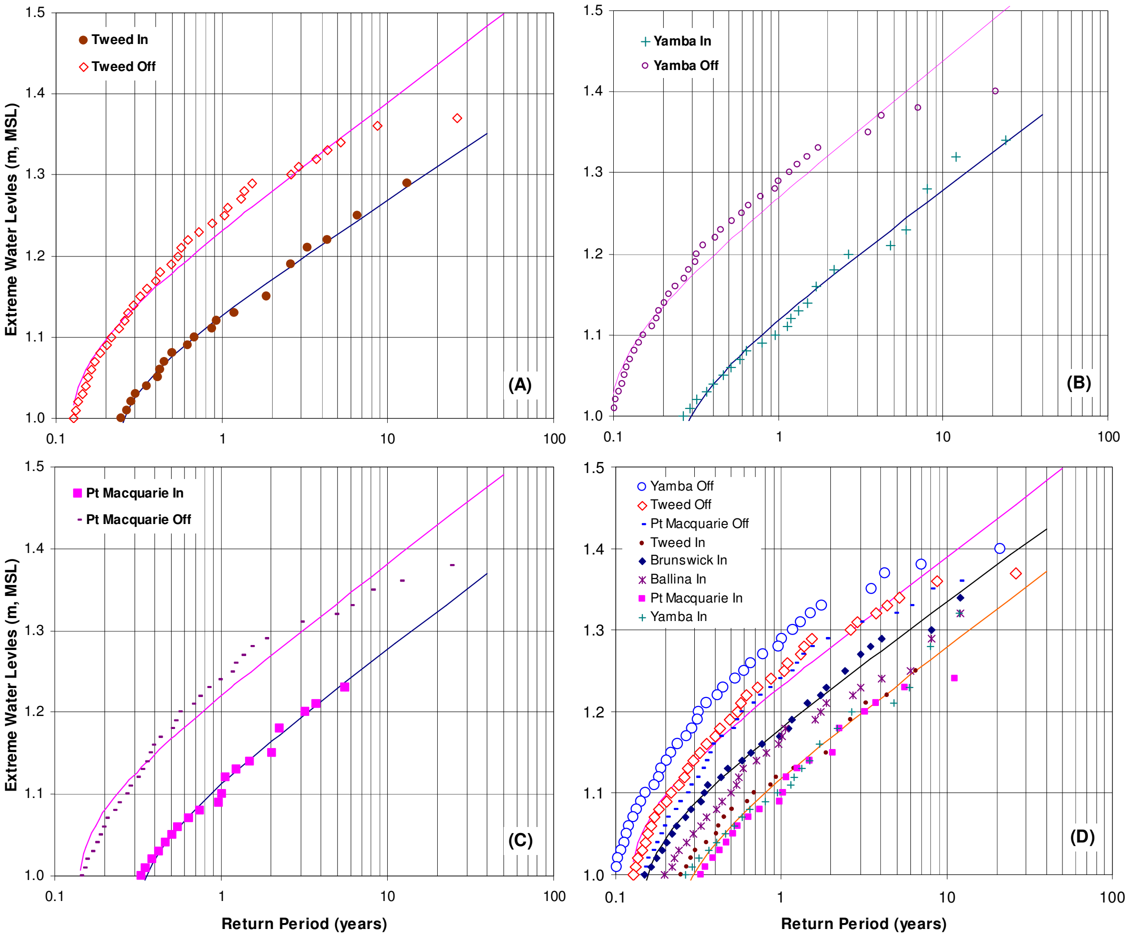

Figure 6:Comparison of the empirical distributions of extreme water levels measured on the northern NSW coast at: [A] the paired inshore and offshore sites of the Tweed River entrance; [B] the paired inshore and offshore sites of the Yamba River entrance; [C] the paired inshore and offshore sites of the Port Macquarie River entrance; and [D] the river entrances and offshore stations, where the solid line is the FT-I distribution fitted to the offshore and river entrance data.

5 Estimation of Extreme Water Levels

There are few studies undertaken to investigate the effect of wave setup on extreme water levels at coastal river entrances. The study of extreme entrance water levels is also of practical engineering importance in modeling of rainfall-related river flooding in tidal floodplains. For example, estimates of extreme water levels at a coastal river mouth can be used as the downstream boundary conditions for modeling of river flooding associated with major rainfall events. The general procedure for estimation of extreme water levels was detailed by You (2012). The FT-I extreme-value distribution function, which was selected from a number of candidate extreme-value distributions by You (2012), is also applied for estimation of extreme water levels in this study. The probability Q of exceeding for extreme water levels equal to or larger than an arbitrary water level H can be computed from the FT-I

$$Q(H) = 1 - \exp\left[-\exp\left(-\frac{H-\beta}{\alpha}\right)\right], \tag{3}$$

where α and β are called the scale and location parameters. In general, there are three main methods used to estimate the distribution parameters, namely, the method of Moments (MM), the Least-Squares method and the Maximum Likelihood method (ML). Carter and Challenor (1983) compared the three parameter estimators and found no one obviously better in estimating the parameters of the FT-I. In a most recent study of Mazas and Hamm (2011), the ML was preferred to the LS, but the ML was found to be less accurate than the LS in estimating the parameters of three-parameter distribution functions such as the Weibull and the Pearson-III. The LS is preferred by several researchers (e.g. Goda, 1988; Kamphuis, 2000; You, 2007) to the MM and ML methods for determination of the distribution parameters. One major drawback for the LS method, which may have been considered by many researchers, is that the plotting positions are required for calculation of the empirical distribution before the distribution parameters can be estimated. The ML and MM methods can directly estimate the distribution parameters without requiring the plotting position formula Eq.(1), but the ML and MM methods still requires the empirical distribution to generate the return water level data before the measured and predicted extreme water levels can be compared. In other words, the empirical distribution in Eq.(1) is required by all parameter estimators directly or indirectly.

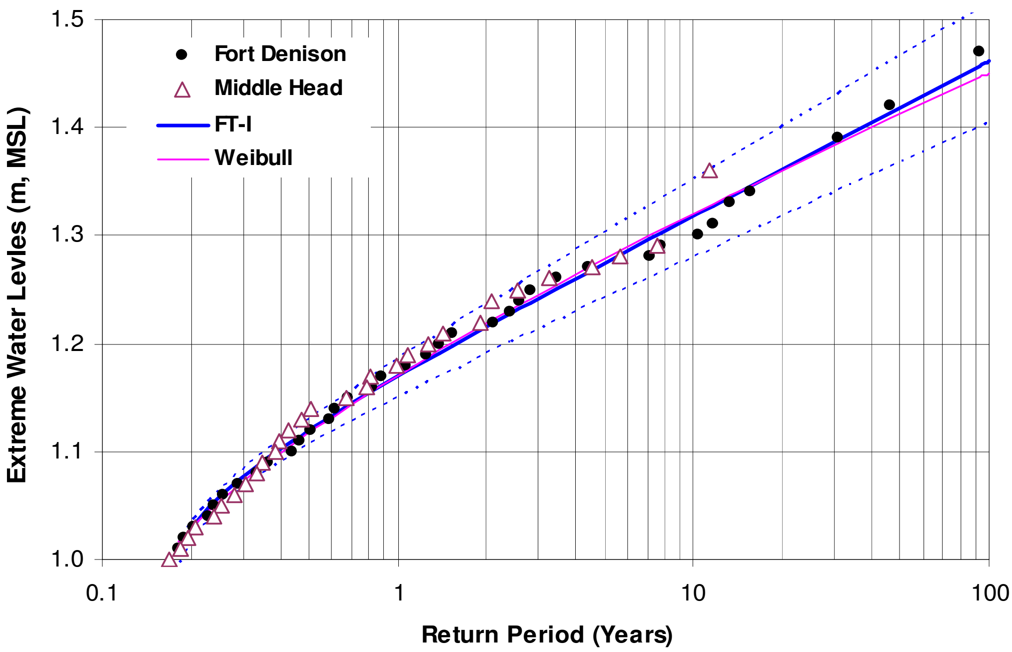

Figure 7: The FT extreme-value distribution is applied to estimate *n*-year return water levels from the monthly maximum water levels collected at Fort Denison inside Sydney Harbor, where the data at Middle Head inside the same Harbor are plotted for comparison, where the Weibull is also included.

The return period T_R is defined in Eq.(2) as an average time interval between successive events of a design water level being equaled or exceeded. For example, if a design water level of 1.3m is equaled to or exceeded by three extreme water levels (1.3m, 1.45m, 1.5m) over a period of 30 years, the return period of the 1.3m design water level is T_R=10 years or the 10-year return water level is H_R=1.3m. For a given value of T_R, the probability of exceeding Q can be estimated directly from Eq.(2) and thus the return water level H_R can be now extrapolated from Eq.(3)

$$H_R = \alpha X_R + \beta \quad \text{and} \quad X_R = -\ln\left[-\ln\left(1 - \tfrac{1}{\lambda T_R}\right)\right]. \tag{4}$$

Figure 7 shows the comparison of the return water levels measured and predicted by Eq.(4) at Fort Denison inside Sydney Harbor, where the data collected at Middle Head with the same harbour are also plotted for comparison. The 95% confidence intervals are empirically estimated as (Gumbel, 1958; CEM, 2009)

$$H(T_R) = \overline{H} \pm 1.96\left[0.487 + 0.889\mathrm{X} + 0.669[\mathrm{X} - 0.577]^2\right]^{0.5} \frac{\sigma_H}{\sqrt{m}}, \tag{5}$$

where $\mathrm{X} = \ln(\lambda T_R)$, m is the total number of monthly water level maxima observed and σ_H is the standard deviation of the observed monthly water level maxima. The empirical formula Eq.(5) derived from the method of moment is used to approximate the 95% confidence intervals for the return water levels calculated from the least-squares method in Figure.7. It can be seen that the return water levels computed from the FT-I agree well with those measured at both Middle Head and Fort Denison inside Sydney Harbor. You (2012) also found the FT-I to be the suitable distribution function for the calculation of extreme water levels at the other stations on the NSW coast. A three-parameter Weibull distribution is fitted to the data in Figure 7, but shown not be better in estimating extreme water levels than the simple two-parameter FT-I.

6 DISCUSSION

Previous field studies of wave setup on natural beaches and at river entrances on the NSW coast (e.g. Nielsen, 1988; Hanslow et al, 1992, 1996), have indicated that whilst wave setup on beaches is significant, little wave setup is seen in trained river entrances like the Brunswick River. The current analysis is basically consistent with the earlier work showing that mean water levels at the trained river entrance sites are not elevated above the offshore levels. On the contrary, the data suggest that the river entrance water levels are lower than those seen offshore. The lower mean water level at the trained river entrances is likely to due to the attenuation in tidal range through the river entrances.

All the river entrance sites investigated in this study are on moderately large trained river systems and all have significant wave breaking at their entrances during coastal storms (and on occasions even in relatively moderate conditions). These river entrances are relatively deep compared with smaller creeks and estuaries. It is probable that the trained entrance water depths in these systems are too deep to generate any wave setup. In comparison with a natural sandy beach, the flatted seabed or nearly constant water depth in the surf zone may be another key factor for little wave setup to be generated at the trained river entrance. Additionally, the presence of training walls, which are often extended deeply into the surface zone, may introduce a physical barrier to higher mean water levels from wave setup on the neighboring sandy beaches (Hanslow and Nielsen, 1992).

The results of this study may not be applicable at smaller coastal systems (e.g. lagoons or creeks) where water depths may become shallow enough to allow wave setup or in untrained river systems there is no physical barrier between the beach/swash zone and the entrance. Care should be used in any extrapolation of the results to return periods significantly beyond the current record lengths due to the potential importance of decadal scale variability which is known to influence both sea level and storm wave climate in SE Australia.

5. CONCLUSION

The extensive field data on mean water levels collected at both inshore and offshore tide stations along the Australian East Coast of New South Wales are used to examine the combined effects of waves and tides on elevated water levels at trained river entrances and also to estimate entrance extreme water levels without rainfall-related entrance flooding. The study of rainfall/runoff on elevated entrance water levels is not included in this study.

The results show that extreme water levels vary along the NSW coast and generally tend to be slightly higher on the north coast than on the south coast. This trend is seen in both bay/harbour sites and river entrance sites. The water levels tend to be lower at the river entrances than at the bay and harbour sites. The comparison between extreme water levels measured at the north coast river entrance gauges and the offshore gauges shows that the extreme water levels at the trained river entrances are consistently lower than those measured offshore, suggesting tidal attenuation between the offshore and river sites. These results also suggest wave setup is not a significant factor at the trained river entrance sites, and are consistent with earlier studies on the trained entrance of the Brunswick River. The estimates of extreme water levels computed at the trained river entrances may also be useful for coastal structure designs and coastal inundation studies on the NSW coast.

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