ESTIMATION OF EXTREME WATER LEVELS AT NSW COASTAL ENTRANCES

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ABSTRACT

Water level data collected along the NSW coast are briefly discussed and analyzed for estimation of extreme water levels at the coastal entrances under the condition of no major entrance floods. The coastal water level data have been continuously collected every 15min at 17 permanent inshore tide stations and 60min at 5 permanent offshore tide stations. Different locally established datums, which were used to collect the inshore water level data, are all converted to the Mean Sea Level datum (MSL) to make the inshore data directly comparable. The offshore water level data were collected relative to the MSL. The Peaks-Over-Threshold method (POT) is applied to obtain statistically independent extreme water level data that consist of monthly maximum water levels larger than 1m. The use of the 1m threshold height has ensured statistical independence of extreme water level data generated. Based on the inshore and offshore extreme water level data, it is found that (i) the offshore extreme water levels are generally similar to those at the inshore stations that are directly exposed to coastal waves; (ii) the extreme water levels measured at Fort Denison inside Sydney Harbour, where coastal waves become insignificant, are almost equal to or larger (up to 10cm) than those at the inshore locations that are not directly exposed to coastal waves, and thus wave setup may become insignificant at the trained coastal entrances; and (iii) the inshore extreme water level data without the outliers of major entrance flood events are best described by the FT-I distribution, and the 100-year return water level at Fort Denison inside Sydney Harbour is estimated to be 1.46 (m, MSL). The conclusions drawn from this study may not be applicable to those untrained coastal entrances.

INTRODUCTION

Coastal inundation can take place in low lying coastal regions for periods of hours to even days over many kilometres of a coastline. This would place coastal properties, infrastructure and human lives at risk, and could also affect business activity and financial security of the regions. In addition, elevated coastal water levels will accelerate beach erosion and further damage coastal ecosystems such as wetlands and mangroves. Therefore, the accurate prediction of extreme water levels is of enormous engineering, economical, ecological and social importance.

NSW coastal water level data have been continuously collected at 17 inshore and 5 offshore tide stations along the coastline since 1982. The locations of the permanent ocean tide stations are illustrated in Fig.1, together with those of 7 permanent wave stations. The collection of wave data along the NSW coast was undertaken after the 1976 severe coastal storm. The water levels at the inshore tide stations were collected every 15 minutes and at the offshore tide stations every 1 hour. The inshore water levels were measured with different locally established datums. There was no absolute datum established for the offshore tide stations and the offshore water levels were measured relative to the local Mean Sea Level (MSL), which is averaged over the period of individual field deployment. The water level data collected at the inshore tide stations may be expected to be much more affected by storm surges, wave setup and other driving forces than those at the offshore stations. The NSW coastal water level data have been collected to study ocean tide anomalies and to provide the offshore boundary conditions for numerically simulating of individual coastal flood events.

In this study, the NSW coastal water level data are briefly discussed and analyzed to compute extreme water levels at the coastal entrances under the conditions of no major entrance floods. The inshore water levels data collected with different datums will be converted to the MSL datum to make the inshore and offshore data directly comparable. The Peaks-Over-Threshold method (POT) is used to generate statistically independent monthly maximum water level data from time-series water level records. Proper extreme-value distributions are then selected to extrapolate the field data to extreme water levels at the NSW coastal entrances.

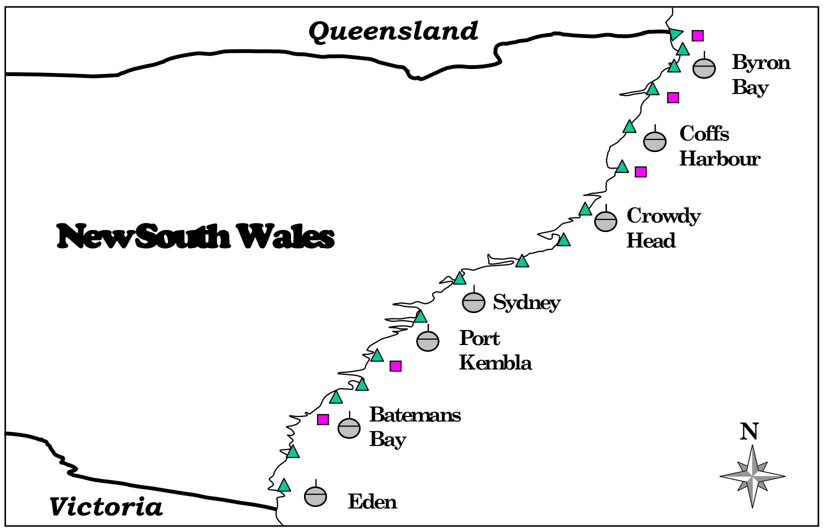

Fig.1. Coastal water level data collected at 17 inshore (Δ), and 5 offshore (□) permanent tide stations and wave data at 7 locations along the NSW coast.

NSW COASTAL WATER LEVEL DATA

Locations

There are 17 inshore and 5 offshore permanent ocean tide stations deployed along the NSW coast as illustrated in Fig.1. The 17 inshore tide gauges were mounted at Breakwaters, Jetties, Wharfs, or inside harbors in shallow waters. The five offshore pressure transducers were installed on heavy steel tripods sitting on the seabed, and located 1.4~3.5km from the shoreline in the water depths of 22~28m. The location detail, data length, gauge type and datum of the tide stations are described in Table-1. The detailed description of the locations can be found in MHL (2009). The water level data collected at the offshore tide stations are expected to be less affected by the nearshore processes such as wave setup and storm surge than those at the inshore stations.

Instruments and Sampling

Three different types of instruments were used to collect the water level data at the 22 inshore and offshore tide stations along the NSW coast, namely, electromagnetic tide gauges, pressure transducers and float-well tide gauges. The pressure transducers are used to collect the offshore water level data at the 5 offshore stations while the electromagnetic and float-well gauges are applied to measure the inshore water level data at the17 inshore stations.

The electromagnetic gauges collected the water levels at 1Hz or 2Hz for 1min or 15min every 15min. The gauges recorded the 1min or 15min averaged water levels every 15min continuously. The water level data were normally 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 14 of the 17 inshore stations were collected by the electromagnetic tide gauges. The pressure transducers recorded 40-second averaged water levels every hour and stored the water level data internally. The data were then downloaded to the computer after recovery from the seabed by divers. The offshore water level data were collected at the five sites all by the pressure transducers.

The float-well gauge recorded the water levels at 0.1Hz 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 can retain up to six months of data. The data were either returned to MHL at the end of a field deployment or downloaded in the field by a portable computer. The water level data at 4 of the 17 inshore stations were collected by the float-well gauges.

Table-1 Description of gauge location, starting date, gauge type and sampling method for 17 inshore and 5 offshore tide stations deployed along the NSW coast. Note: Electromagnetic Gauge (EG), Pressure Transducer (PT), and Float Well (FW).

Site Name	**Starting Date**	**Location**	**Gauge Type**	**Sampling Rate (Hz)**	**Sampling Length (min)**	**Sampling Interval (min)**	**Station Datum**
Tweed Heads	1987	Breakwater	EG	2Hz	1	15	Tweed River Hydro Datum
Tweed Heads Offshore	1982	3.5km offshore 28m depth	PT	Integrated	40sec	60	Local mean sea level
Brunswick Heads	1988	Training wall	FW	0.1Hz	160sec	15	Brunswick River Flood Mitigation Datum
Ballina	1986	Breakwater	EG	1Hz	15	15	Low Water Ordinary Spring Tide
Yamba	1986	Breakwater	EG	1Hz	15	15	Port Datum
Yamba Offshore	1987–2005	1.9km offshore 23m depth	PT	Integrated	40sec	60	Local mean sea level
Coffs Harbour	1987	Inside Harbor	EG	2Hz	1	15	Coffs Port Datum
Port Macquarie	1986	Breakwater	FW	0.1Hz	160sec	15	AHD
Port Macquarie Offshore	1984	1.4km offshore 22m depth	PT	Integrated	40sec	60	Local mean sea level
Crowdy Head	1986	Inside Harbor	EG	2Hz	1	15	Crowdy Head Datum
Forster	1986	Breakwater	EG	1Hz	15	15	Forster Hydro Datum
Port Stephens	1985	Jetty	FW	0.1Hz	160sec	15	Port Stephens Hydro Datum
Sydney	1987	Middle Head	EG	1Hz	15	15	Indian Spring Low Water
Port Hacking	1988	Hungary Point	EG	2Hz	1	15	Indian Spring Low Water
Shoalhaven Heads	1991	Northern end of SH	EG	1Hz	15	15	AHD
Shoalhaven Offshore	2005	2km offshore, at 25m depth	PT	Integrated	40sec	60	Local Mean sea level
Crookhaven Heads	1991	100m from Jetty	EG	1Hz	15	15	AHD
Jervis Bay	1989	HMAS Creswell	EG	1Hz	15	15	Chart Datum
Ulladulla	2007	Jetty	EG	1Hz	15	15	AHD
Batemans Bay Offshore	2000	250m offshore 28m depth	PT	Integrated	40sec	60	Local mean sea level
Bermagui	1987	Jetty	FW	0.1Hz	160sec	15	Bermagui Local Hydro Datum
Eden	1986	Wharf	EG	2Hz	1	15	Twofold bay Hydro Datum

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, different local datums are all converted to the local Mean Sea Level datum (MSL) under the assumption that the local MSL datum, which is averaged over a long timescale of decades, may not significantly vary spatially from station to station. The water level data recorded with the locally established datums are converted to the water levels relative to the local MSL datum by summating all water level data together and then dividing the summation by the total number of data to obtain the mean water level and finally subtracting the mean water level from individual water levels to obtain the water level data relative to the MSL.

No absolute local datum was established for the offshore tide stations. Thus, the local MSL, which was averaged over the length of individual field deployment, was adopted for the offshore stations. The local MSL is expected to vary slightly from station to station, depending on the duration of the field deployment and on meteorological and oceanographic conditions. However, this variation in the local MSL datums is expected to be insignificant. It is also assumed that the inshore and offshore local MSLs are almost equal even though they may be slightly different.

Water Level Data

The NSW coastal water level data have been collected continuously every 15min at the inshore stations and every 1hr at the offshore stations. Fig.2 shows a segment of time-series water level record collected at Fort Denison inside Sydney Harbour. The measured total water level consists of astronomical tide and tidal residual. Astronomical tides on the NSW coast are semi-diurnal. The tidal range, which is the difference in heights between high and low waters over about 12hr, varies in a cycle of about two weeks and is up to 2m (see Fig.2). The tidal residual is generated by meteorological and oceanographic drivers such as storm surge, wave setup, seiche, longshore wind setup, coastal long waves, El Nino and sea level rise. The time-series water level data collected at the inshore and offshore stations will be analysed to obtain statistically independent extreme water level data.

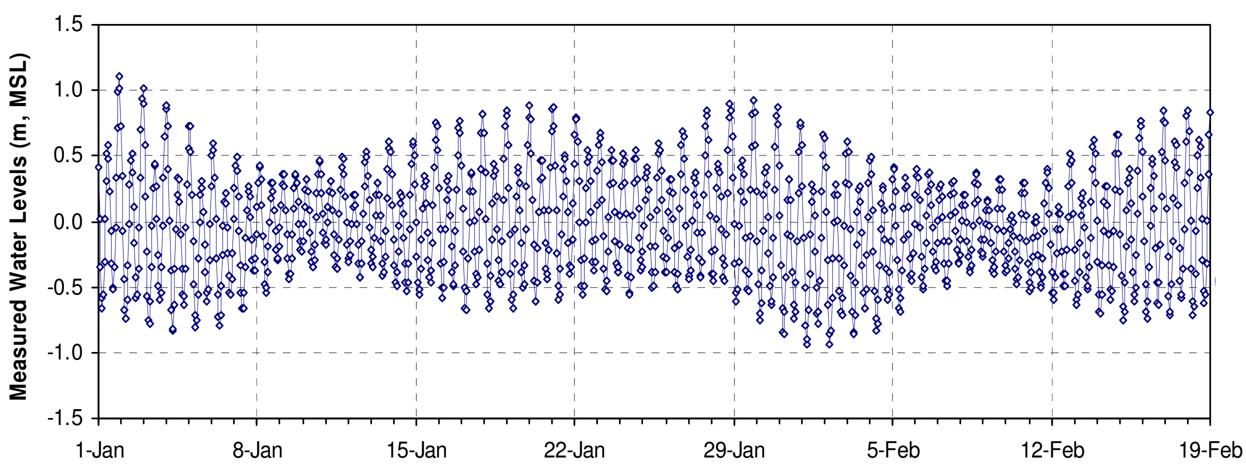

Fig.2. A segment of time-series water level record collected every 15min at Fort Denison inside Sydney Harbour. Tides are semi-diurnal and the tidal range is up to 2m and the measured total water levels are generally dominated by astronomical tides.

ESTIMATION OF EXTREME WATER LEVELS

Approach

The basic approach used to estimate extreme water levels is similar to that of You (2007) applied to calculate extreme wave heights. The approach may consist of six steps: (1) Generating a sample of statistically independent extreme water levels from a historical time-series water level record; (2) Computing the empirical distribution of extreme water levels and return water level data; (3) Selecting proper candidate distribution functions for extrapolation of the empirical distribution or the return water level data; (4) Estimating the parameters of candidate distribution functions selected; (5) Determining the best-fit distribution function of the selected distributions, and (6) Calculating extreme water levels from the best-fitted distribution with confidence.

Extreme Water Level Data

The Peaks-Over-Threshold method (POT), which has been most commonly used for extreme wave analysis (You, 2007), is also applied to generate statistically independent extreme water level data. In this study, monthly maximum water levels, which are also required to be higher than 1m, are extracted from time-series water level record to obtain a sample of extreme water levels. The 1m threshold height is taken to be approximately equal to or slightly larger than the maximum amplitude of astronomical tides on the NSW coast (see Fig.2). The use of the 1m threshold will ensure statistical independence of extreme water level data generated.

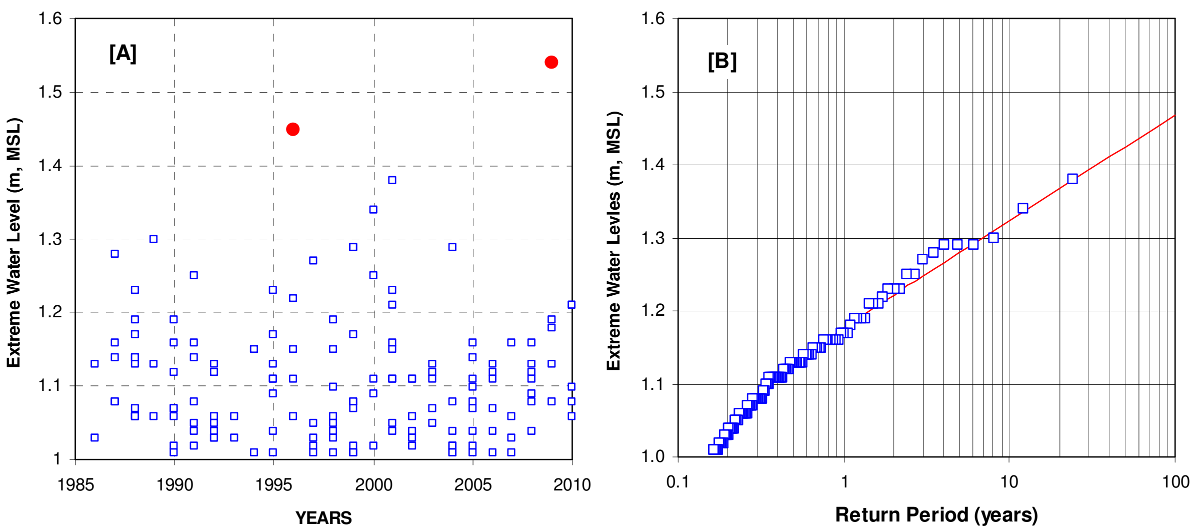

Fig.3 [A] Monthly maximum water levels being larger than 1m are extracted from the time-series water level record collected at Brunswick Head from 1986 to 2010, and the two red dots are defined as *outliers*, and **[B]** the return water level data, derived from the monthly maximum water levels without the outliers, are best fitted by the FT-I distribution.

Fig.3 [A] shows a set of extreme water level data that are extracted from the time-series water level record collected at Brunswick Heads from 1986 to 2010 with the POT method. The number of extreme water levels per year is shown to vary from 2 to 9. The total number of monthly maximum water levels larger than 1m is 152 over the period of 24.3 years, and the average number of extreme water levels per year is λ=6.26. Note the number of monthly maximum water levels larger than 1m per year may not be always equal to 12 because some monthly maxima are less than 1m and thus excluded in the extreme water level data.

The two red dots (1.45m, 1.54m) in Fig.3 [A] are identified as o*utliers*. The outliers are often defined as observed values that are much larger than the other observed values in a sample from the same population. Another outlier, 1.98m in 1986, is not plotted in Fig.3 [A]. The outliers were recorded at the inshore stations when the coastal entrances were flooded. No outliers are found from the offshore data. The extreme water level data without the outliers in Fig.3 [B] are shown to be best described by the FT-I. The exclusion of the outliers in Fig.3 [B] means that estimates of extreme water levels at the river entrance of Brunswick Heads, which are extrapolated from the best-fit FT-I distribution, don't include the effects of major entrance floods.

Empirical distribution

The empirical distribution of extreme water levels may be estimated from ranked monthly maximum water levels as

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

where n is the n^{th} monthly maximum water levels ranked in descending order, and m is the total number of monthly maximum water levels observed. Eq.(1) is consistent with the definition of the return period T_R (You, 2012)

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

where $Q=n/m$, $\lambda=m/T$, and T is the record length. Eq.(1) is only the plotting position formula that is consistent with the definition of the return period $T_R=T/n$. Note that when Q=1 or $n=m$ in Eq.(1), most extreme-value distribution functions become invalid and thus the lowest water level or the last date point in the dataset will be excluded for calculation of extreme water levels, but this limit will not affect the accuracy of estimated extreme water levels. Eq.(2), which is derived from the empirical distribution in Eq.(1), will be used to generate the return water level data that are required to compare with those predicted from extreme-value distribution functions. The return water level data at the coastal river entrance of Brunswick Heads are derived from Eq.(2) and shown in Fig.3 [B]. In fact, the data on the empirical distribution (Q, H) are equivalent to the data on the return water level (T_R, H) simply because m and T are all constant in Eqs.(1) and (2).

Extreme-Value Distribution Functions

Several extreme-value distribution functions (e.g. FT-I, II and III, Lognormal, Pearson-III, and Weibull) may be used to extrapolate monthly maximum water level data to extreme water levels with different return periods. The FT-I distribution has been recommended by CEM (2009) for estimation of extreme water levels. You (2007) and You and Lord (2008) also found that the FT-I is the best-fit distribution for extrapolation of extreme wave heights on the NSW coast. Again, this study has found that the FT-I gives the best fit to the monthly maximum water level data collected at both the inshore and offshore stations. 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. With induction of the reduced variable X, Eq.(3) can be transformed in the linear form of

$$H = \alpha X + \beta \quad \text{and} \quad X = -\ln[-\ln(1-Q)], \tag{4}$$

of which α and β need to be determined from the extreme water level data with a proper parameter estimator.

Distribution Parameter Estimators

Three parameter estimators, the method of moments (MM), the maximum likelihood method (ML) and the least-squares method (LS), are most commonly applied to estimate the distribution parameters in Eq.(4). The LS method may be preferred over the other two methods as discussed recently by You (2012). The main reasons are (1) the LS method is simple to determine the distribution parameters especially for three-parameter distribution functions such as Weibull and Pearson-III, (2) it is easy to visualize the goodness of fit from a linear plot, (3) abnormal data points (not outliers) can be easily identified and subsequently removed from the analysis, and (4) the LS method can easily manipulate extreme water level data to give the best fit to high water levels. One major drawback for the LS method, which may have been commonly considered by many researchers, is that the plotting positions are required for calculation of the empirical probability before the distribution parameters can be estimated. The other two estimators, the ML and MM, can directly estimate the distribution parameters without requiring the plotting positions, but they still requires the plotting positions or Eq.(2) to generate the return water level data before the measured and predicted return water levels can be compared. Thus, all parameter estimators are required to calculate the empirical distribution directly or indirectly.

With the LS method, the distribution parameters (α, β) of the FT-I are uniquely determined in Fig.4 from the water level data collected at Middle Head inside Sydney Harbour and at the coastal river entrance of Brunswick Heads, where α is the slope of the regression line and β the intercept according to Eq.(4). The FT-I is shown to give the excellent fit to the extreme water level data as indicated by the high value of R^2. The distribution of extreme water levels at Middle Head is shown to almost identical to that at the coastal river entrance of Brunswick Heads, and best described by the FT-I distribution. This also indicates that the extreme water level data at the river entrances of Brunswick Heads are not affected significantly by coastal waves.

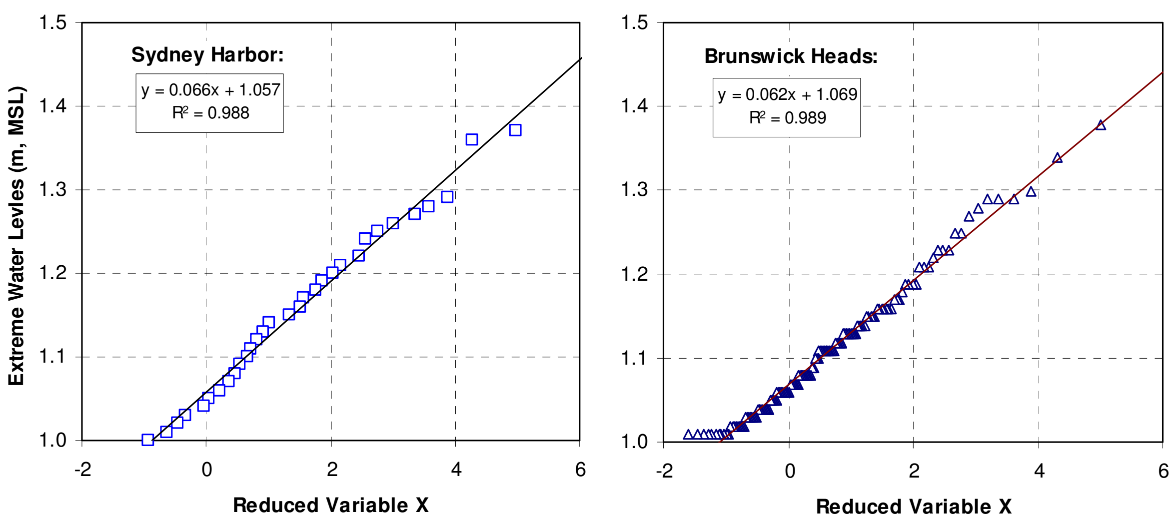

Fig.4 The distribution parameters of the FT-I (α, β) are determined from the water level data collected at Middle Head inside Sydney Harbor and at the coastal river entrance of Brunswick Heads.

NSW Coastal Return Water Levels

The return period T_R is defined 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. 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.(4)

$$H_R = \alpha X_R + \beta \quad \text{and} \quad X_R = -\ln\left[-\ln\left(1 - \tfrac{1}{\lambda T_R}\right)\right]. \qquad (5)$$

The return water levels are then computed from Eq.(5) of the FT-I and compared with those measured at the inshore and offshore stations in Fig.5. The extreme water levels measured at Fort Denison inside Sydney Harbour, which is not directly exposed to coastal waves, are also compared with those collected at the inshore and offshore stations, respectively.

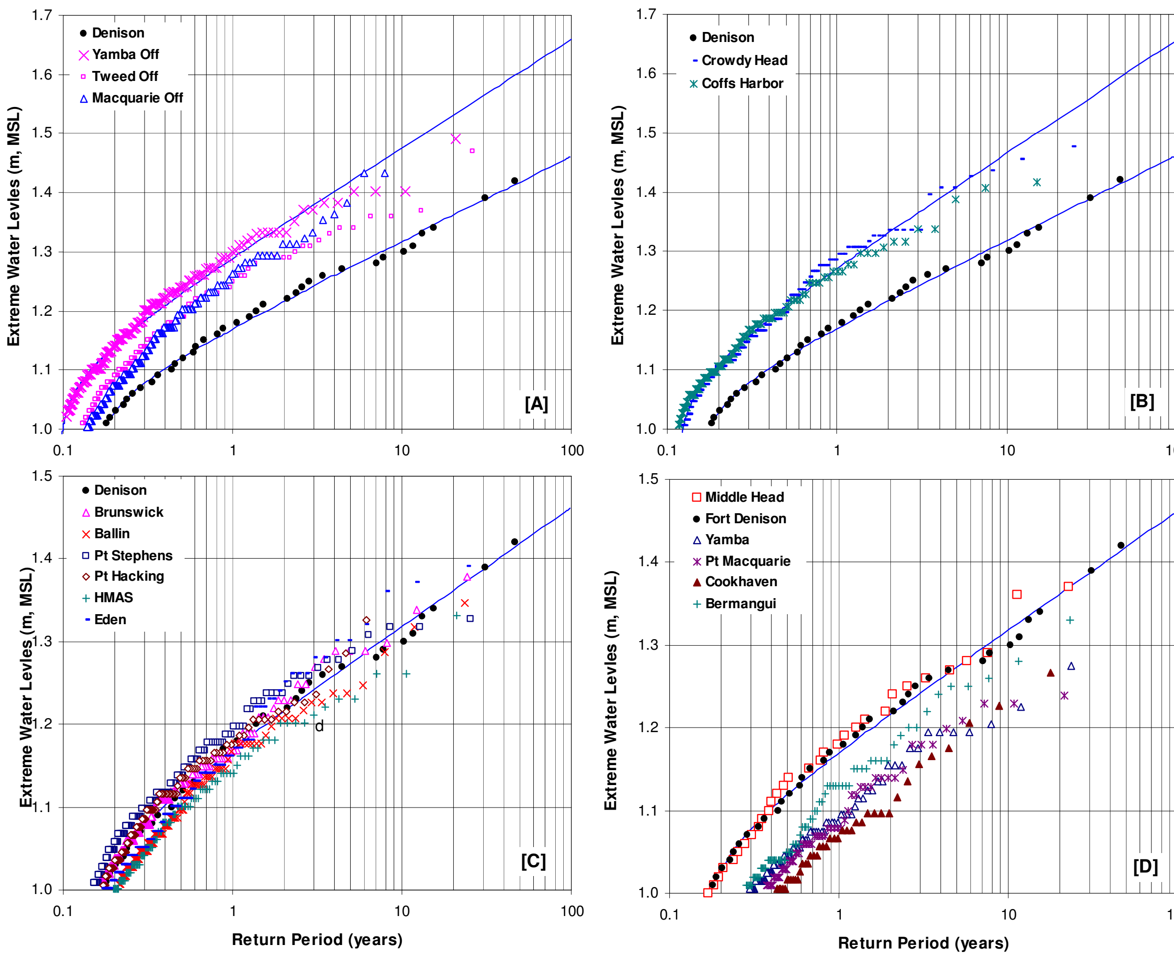

Fig.5 Extreme water levels measured at the inshore and offshore stations along the NSW coast excluding the outliers of major entrance flood events. .

In Fig.5 [A], the difference in the extreme water levels measured at the offshore stations is shown to be minor (e.g. <5cm), and the offshore extreme water levels are higher than those at Fort Denison. This difference may be caused by energy dissipation as tides propagate to the inshore station. In Fig.5 [B], the extreme water levels measured at Coffs Harbour and Crowdy Head, which are directly exposed to coastal waves, are shown to be similar to those at the offshore stations, but higher than those at Fort Denison. In Fig.5 [C], the extreme water levels measured at the six inshore stations from Brunswick in the north to Eden in the south are shown to be approximately equal to those at Fort Denison, but in Fig.5 [D], the extreme water levels at the other four inshore stations are lower (up to 10cm) than at Fort Denison and Middle Head.

CONCLUSION

The extensive NSW coastal water level data are briefly described and analyzed to obtain the distributions of extreme water levels at the NSW coastal entrances under the conditions of no major entrance floods. Different locally established datums, with which the inshore data were measured, are all transformed to the Mean Sea Level datum (MSL) to make the inshore and offshore datasets directly comparable. The Peaks-Over-Threshold (POT) method is used to generate statistically independent extreme water level data. The use of the 1m threshold height has ensured the statistical independence of extreme water level data generated. The outliers, which may be related to major entrance floods, are excluded for the extreme-value analysis. Based on the inshore and offshore extreme water level data obtained in this study, it may be concluded that (i) the offshore extreme water levels are approximately equal to those at the open coastal locations such as Coffs Harbour and Crowdy Bay, but generally larger (about 20~30cm) than those at the trained coastal entrances; (ii) the extreme water levels at both Fort Denison and Middle Head inside Sydney Harbour are generally equal to or higher (up to 10cm) than those at the coastal entrances that are trained and not directly exposed to coastal waves. This also implies that wave setup or other wave-related processes at the trained coastal entrances is insignificant, and (iii) the extreme water levels at the NSW coastal entrances are best fitted by the FT-I distribution, and the 100-year water level at Fort Denison is computed to be 1.46 (m, MSL).The conclusions drawn from this study may not be applicable to those coastal entrances without trained walls.

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