PRELIMINARY EXAMINATION OF COAST AND CATCHMENT FLOODING INTERACTION FROM THE DATA

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Abstract

The interaction of coastal and catchment flooding is important in understanding the envelope of potential flooding in the lower reaches of coastal waterways.

This paper examines the interaction of coast and catchment flooding for a number of different types of coastal waterways in NSW. It presents the results from a preliminary examination that utilises available time series water level data recorded by NSW Public Works' Manly Hydraulics Laboratory (MHL) on behalf of the Office of Environment and Heritage (OEH) from the ocean up to the tidal limit of key estuaries. The key estuaries were chosen based on size, characteristics, geographic location and availability of recorded information. Summary tables were produced to identify the highest magnitude ocean and catchment flooding to assist further analysis and identify significant events. These significant events were presented graphically to look at the coincidence of ocean and catchment flooding and their relative timing.

Introduction

Flooding in tidal waterways can be the result of catchment flooding, coastal flooding or a combination of these factors. However, the interaction of these events can be complex and depends upon a wide range of factors including catchment shape, size and location, waterway configuration including entrance type and available storage configuration, similarities and differences in synoptic types for storms likely to result in flooding and coastal events, the relative timing of the peaks of these events, and the location and vulnerability of the community and associated investment.

To improve our understanding of these issues and their relevance in particular cases, OEH was successful in gaining funding from the Natural Disaster Resilience Program (which provides a combination of State and Commonwealth funding to projects and is managed by the Ministry of Police and Emergency Services in NSW) to examine the coincidence of coastal and catchment flooding more closely.

This enabled OEH to embark on a two-stage project to more closely examine the interaction of catchment and coastal flooding events. This paper is based on work undertaken by MHL toward the completion of Stage 1 of this project, comprising a preliminary assessment of what can be derived from the available gauge data. Stage 2 will involve further research aimed at improving our understanding of the key factors that need to be considered in assessing the likely degree of coincidence between catchment and coastal flooding in particular situations. This work aims to provide improved guidance on consideration of the interaction of coast and catchment flooding in flood planning.

Prior to outlining this preliminary assessment, it is necessary to understand the:

- drivers for coastal flooding and whether these relate to the same synoptic types and storm events likely to cause catchment flooding
- current advice in coincidence of coastal and catchment flooding, and on how coastal inundation occurs and its impacts on tidal waterways.

Drivers for Ocean Conditions likely to influence Flooding in Tidal Waterways

Coastal flooding can significantly influence flooding in tidal waterways due to the influence of downstream boundary conditions and the filling of available storage within the tidal waterway prior to catchment flooding. The propagation of downstream conditions into the tidal waterway can be significantly influenced by the entrance type.

Downstream boundary conditions caused by ocean conditions are an important consideration within flood studies in tidal waterways. These require considerations of ocean tide conditions as well as other contributors to ocean water levels including the effects of waves within river entrances; the likelihood of joint coincidence of elevated entrance water levels with catchment flooding; and the potential importance of event durations and system response time. Translation of these impacts into the waterway can also be significantly influenced by the ocean entrance.

Tides along the NSW coast are semi-diurnal with a significant diurnal inequality. Highest astronomical tide at Sydney is 2.1 m above lowest astronomical tide. The mean spring range is 1.2 m while the mean neap range is 0.8 m (Australian Hydrographic Service, 2011). The mean range at Sydney is 1.0 m with Mean High Water of 0.52 m AHD and Mean Low Water of -0.48 m AHD (MHL, 2011b). Tide range varies along the coast with an increase of around 0.2 m from south to north as shown in Figure 1 (MHL, 2011a).

Variations in water level due to non-astronomic factors (i.e. factors not included in tidal predictions) are common along the NSW coast and associated with a range of oceanographic and meteorological processes. MHL (1992) shows that anomalies of 0.3 m occur at return intervals of months, and thus become a significant addition to tidal predictions. Drivers of tidal anomalies include variations in air pressure and wind stress which during storms is known as storm surge; coastal trapped waves; ocean currents, steric effects; seiches; tsunamis; rossby waves etc. These processes operate over a wide range of time frames.

Studies of the Fort Denison tide record show inter-annual and multi-decadal variability linked with both the El Nino Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO) (Holbrook, 2010; MHL, 2011a). These oscillations see variation in annual mean sea level of around 10 cm. At higher frequencies many factors contribute to anomalies but the largest are associated with storm surge and/or coastal trapped waves. Coastal trapped waves propagate south to north and have wave heights of around 20-30 cm and can elevate coastal water levels for several days (Church et al. 1986a, b; MHL, 2011a).

Storm surge, while smaller than on many coasts worldwide, can still raise water levels above normal by over 50 cm (e.g. NSW Government, 1990). Storm surges can be fairly short lived or last for more prolonged periods (days) depending on storm characteristics and propagation.

Annual anomalies increase from south to north along the coast as illustrated in Figure 2 taken from NSW Ocean Water Levels (MHL, 2011a). Storm surge is usually the largest single contributor to tidal anomalies and extreme ocean levels but joint coincidence with other drivers also needs to be considered.

Within river entrances water depth and entrance morphology play a significant role in modifying tidal behaviour while wave breaking may also influence mean water levels through wave setup. These effects are likely to vary significantly between different waterway types, with entrance type and entrance depth playing a significant role.

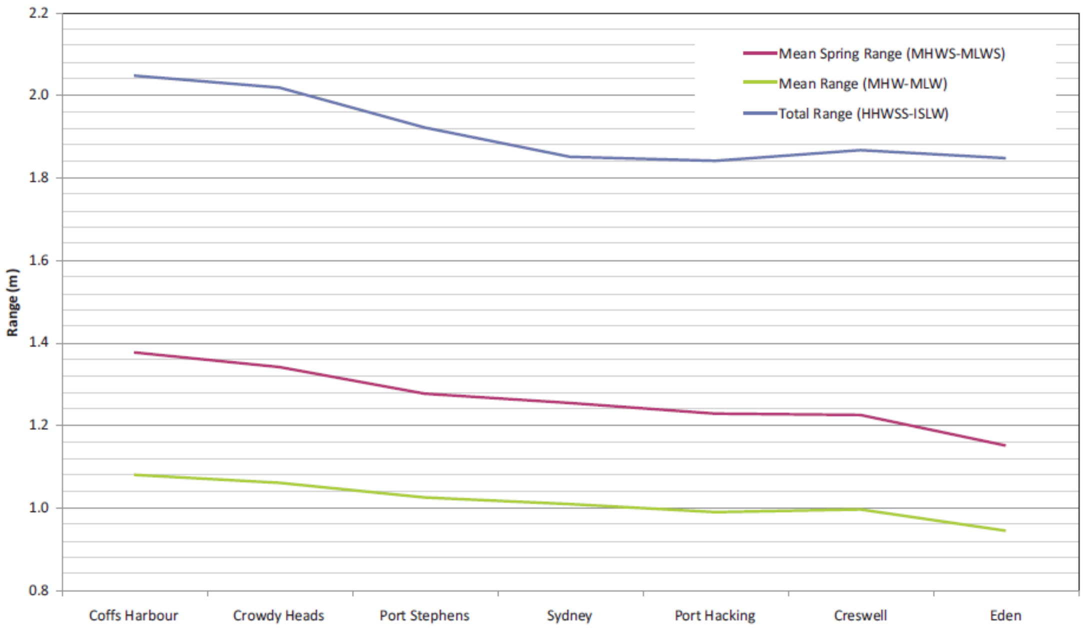

Figure 1: NSW tide ranges*# source MHL 2011a*

Within tidal rivers, initial tidal attenuation is usually followed by mild amplification. In drowned river valleys landward narrowing of the channel promotes amplification, while in larger coastal lakes entrance shoaling results in rapid attenuation of tide range (e.g. Figure 3). In these systems resonance of longer period tidal constituents results in growth in the size of the fortnightly tidal signal which can become as large, or larger than the semi-diurnal tide.

Wave setup on beaches results in significant super elevation of mean water levels particularly near the beach face, however water depth in most river entrances is likely to mean wave setup is significantly lower than on beaches. Measurements from the Brunswick River entrance in northern NSW suggest wave setup is minor within moderate sized trained river entrances (e.g. Nielsen and Hanslow, 1995). Wave setup may, however, play a more significant role in shallower entrances.

Obviously many of the factors that contribute to ocean water levels are independent of rainfall, thus their joint coincidence is not forced but nevertheless needs to be considered in a probabilistic context.

Storm surge-related tidal anomalies may, however, be generated by weather phenomena that also contribute to coastal rainfall and potentially flooding, thus considerations concerning joint coincidence become more important. For these events, however, numerous questions need to be examined. These concern the:

- influence of ocean conditions on the tidal waterway.
- relative scale of coastal and catchment flooding events.
- relative timing of peak rainfall and flood relative to the peak of ocean conditions.
- type of storm cell (synoptic type) that is likely to lead to significant catchment flooding and/or significant coastal flooding and whether this is the same.
- importance of the catchment size, shape and available waterway volume.
- relative location of the community in relation to the waterway and its entrance.

Several studies have identified the synoptic storm types critical to the generation of extreme wave and water level conditions along the NSW coast (Shand et al., 2011; Blain Bremner and Williams, 1985). These appear to have much in common with those identified as contributing to heavy rain events (e.g. Speer et al., 2009). Speer et al. (2009) notes that systems that develop within subtropical easterly wind regimes,

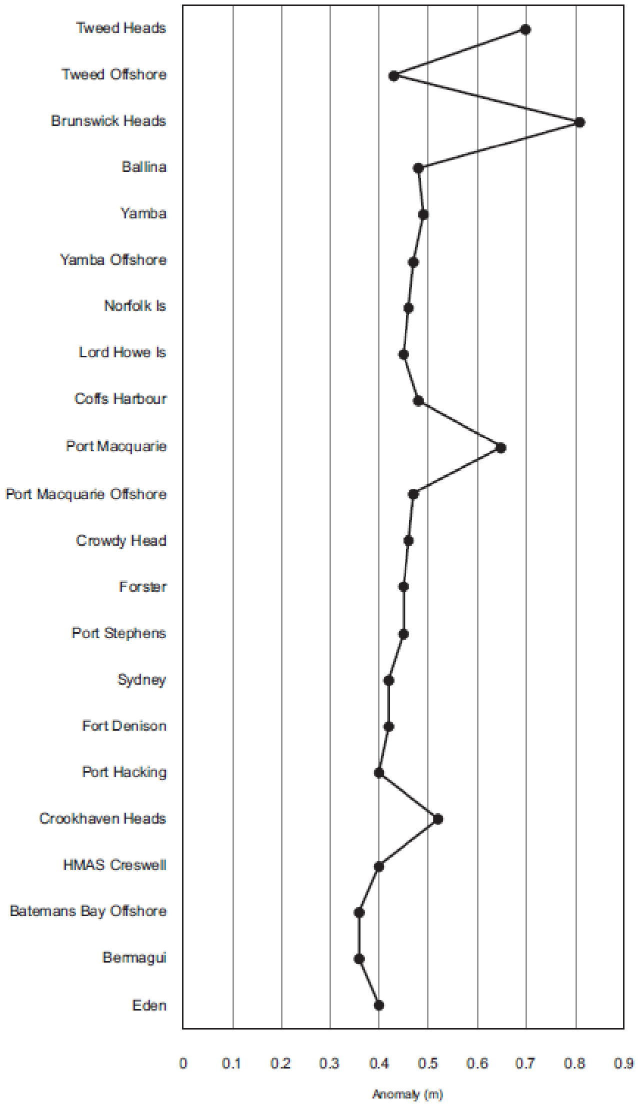

Figure 2: NSW ocean gauge 1-yr annual recurrence of tidal anomalies*# source MHL 2011a*

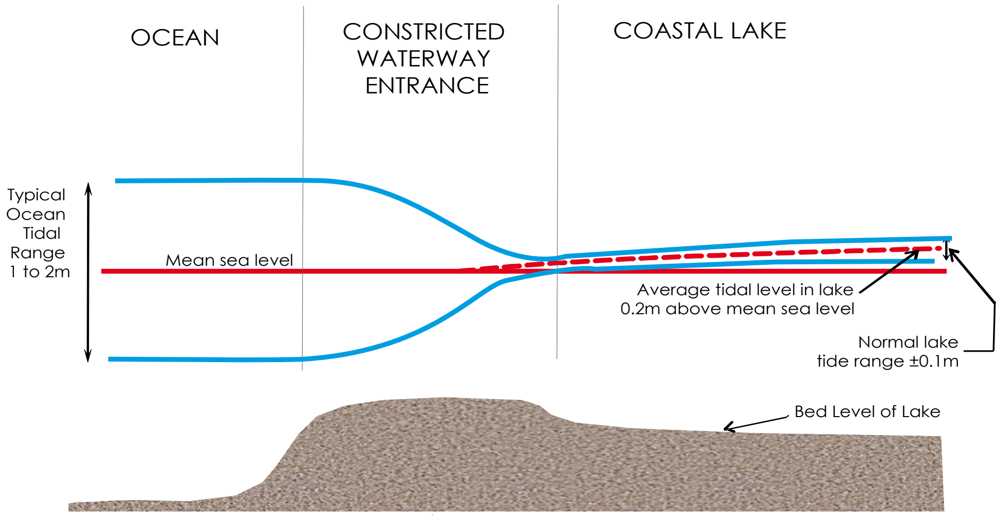

Figure 3: Example of Entrance Impact on Tidal Ranges in an Open Coastal Lake with a Constricted Entrance*# source McLuckie et al 2010*

namely inland trough lows and easterly trough lows, account for 71 percent of the significant rain events when combined with the ex-tropical cyclone category and 84 percent of the heavy rain events. These types also make up a significant proportion of the synoptic types resulting in wave heights over 5 m along the NSW coast (Shand et al., 2011). These studies did not examine whether rainfall led to flooding nor did they consider shorter duration events, such as thunderstorms, that may influence flooding in small coastal systems.

Current Advice on Coincidence of Coastal and Catchment Flooding

The significance of coastal and catchment flooding on tidal waterways and their combination will vary with location, the characteristics of the waterway and the relative vulnerability of the surrounding communities.

To determine conditions relevant for flood planning for the 1% AEP (or 100-year ARI) flood in coastal waterways OEH recommends the assessment of a number of combinations of events to define the critical conditions (peak water levels and velocities) for management. This envelope approach involves examining the following combination of events:

- 1% AEP catchment flooding with 5% AEP coastal flooding
- 1% AEP catchment flooding with neap tide conditions in the coastal waterway to provide an understanding of potential flow velocities
- 5% AEP catchment flooding with 1% AEP coastal flooding
- no catchment flooding with 1% AEP coastal flooding.

Figure 4 provides a simplistic illustration of these events.

The NSW Government's flood risk management guideline on considering sea level rise in flood risk assessments also provides advice on the downstream conditions to use for the coastal flooding portion of these assessments. Whilst ideally all assessments would involve a site specific assessment of coastal flooding based upon derived downstream boundary conditions, this may not be necessary where the location of development is not particularly vulnerable to flood impacts. Therefore the guideline also provides several simpler conservative methods that can be considered where the flood risk is likely to be limited even using more conservative approaches, and the additional cost of a detailed assessment is not considered warranted.

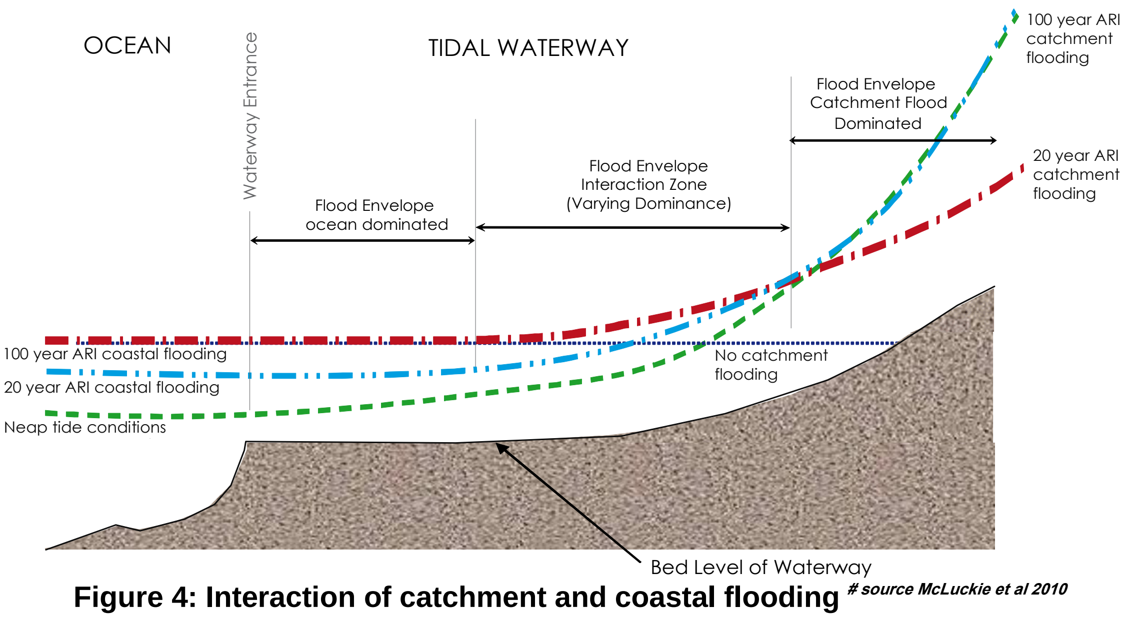

Figure 4: Interaction of catchment and coastal flooding *# source McLuckie et al 2010*

However, where these conservative assumptions are expected to have significant impacts upon the community or significantly add to cost of development, a more detailed site specific assessment is recommended. It should be noted that studies undertaken under the Floodplain Management Program are expected to use a detailed site specific assessment unless specifically agreed to by OEH.

The work from this project (Stage 1) and its subsequent stage is likely to enable a review of the current simplistic conservative approaches to enable better advice to be provided for a range of tidal waterways. It may also provide some additional advice to assist with detailed site specific assessments, but will not remove the need for such assessments.

In addition to this advice, it is understood that the update of Australian Rainfall and Runoff is likely to provide advice on the coincidence of coastal and catchment flooding, based upon available national datasets. This work examines the coincidence of rainfall and tidal anomalies in assessing the potential for coincidence of coastal and catchment flooding. Whilst this provides a good starting point for understanding coincidence:

- rainfall may not lead to flooding. The significance of catchment flooding is influenced by antecedent catchment and waterway conditions, areal distribution of rainfall relative to the catchment, storm duration relative to critical duration and the intensity of rainfall, among other factors
- the existence of a tidal anomaly may not result in significant peak ocean levels and lead to coastal flooding. Many anomalies occur within the neap portion of the tide
- the timing of any catchment and coastal flooding arising from the rainfall and tidal anomaly may not coincide.

The significant investment of the NSW Government in riverine, estuarine and coastal water level gauging networks provides an opportunity to examine this coincidence more closely and may provide the potential to enhance the advice available on the coincidence of coast and catchment flooding within NSW. Stage 1 of this project provides a preliminary examination of this data at a range of key locations.

Stage 1 Assessment

Stage 1 of this project involves a preliminary assessment of what understanding of the coincidence of coastal and catchment flooding can be derived from the examination of available gauge data for a range of different tidal waterways in NSW.

It aims to provide a better understanding of the coincidence of coastal and catchment flooding in NSW and provide key information for consideration in Stage 2, which will involve further research.

Stage 1 involves the compilation and analysis of water level data from the NSW Public Works' Manly Hydraulics Laboratory (MHL) database and various other sources of information in order to determine what the available recorded data can tell us about the coincidence of catchment and coastal flooding.

This involved several phases. These were:

- preliminary examination to understand the relevant data that was available in rivers, estuaries and on the coast and its limitations
- examination of the different types of tidal waterways and the selection of waterways for further assessment as part of this project
- trial of and refinement of a methodology for assessment of the potential for coincidence of coastal and catchment flooding on a system
- application of trial methodology to other tidal waterways including both similar and different types.

These phases of the investigation are discussed below. This is followed by a discussion of the preliminary results of this investigation and recommendations for additional works as part of Stage 2 of the project.

Preliminary Examination of the Data

MHL maintains an extensive water level database from 250 estuary and river water level gauges, 19 ocean tide gauges and 7 ocean wave buoys for all 107 NSW coastal basins with over 30 years of data at some sites that served as the primary source of information for use in Stage 1. Data availability and estuary characteristics from the OEH website (http://www.environment.nsw.gov.au/estuaries/list.htm) guided the preliminary selection of 26 estuaries appropriate for investigation, based on the variation in estuary and entrance types, sizes and geographic location. Characteristics of the selected tidal waterways and their locations are shown in Table 1 and Figure 5.

The synoptic storm type associated with identified flood events in this study was based on the NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves (Shand et al., 2011). This data set has limitations as the storms causing catchment flooding and/or ocean anomaly may not cause large wave heights and vice versa and the date of reported storms is based on the peak Hs at a wave buoy and may not affect the specific waterway or may affect it on a different date. Flood studies for each of the waterways were sought to provide design flood levels to give a relative context to the size of the recorded floods within the data record.

Figure 5: Preliminary waterway locations

Selected Tidal Waterways

The top 20 to 30 flood events at each chosen waterway were correlated with daily peak ocean levels and anomalies at the appropriate ocean water level station to help determine suitability for further analysis.

The preliminary data assessment informed the selection of eight estuaries with suitably long historical data records (20 to 30 years), and with a number of floods on record, for more detailed analysis. The selection of estuaries of varying type, size and location was limited by the need to analyse sites with significant floods on record.

The vast majority of estuaries in NSW are wave-dominated barrier estuaries (54) and intermittent estuaries (110) (Roy et al., 2001). Only one intermittent estuary, Narrabeen Lagoon, was selected in this study as the magnitude of flooding in such estuaries is generally dominated by the condition of the entrance, and the periods of water level record available are relatively short. The remaining seven sites are wave-dominated barrier estuaries spread geographically along the NSW coast and with varying size and

Table 1: Characteristics of estuaries for preliminary investigation

Entrance	Catchment size (km^2)	Estuary area (km^2)	Estuary volume (10^6 m^3)	Average depth (m)	Estuary group	Estuary type	Ebb flow (10^6 m^3)	Flood flow (10^6 m^3)	MHL stations
Tweed River	1054.8	22.7	56954.6	2.6	WDE	BE	13.49	6.91	10
Brunswick River	226.3	3.6	4267.9	1.3	WDE	BE	2.08	2	5
Richmond River	6862	38	119314.4	3.2	WDE	BE	21.9	24.99	7
Evans River	75.8	2.7	2636.8	1.1	WDE	IBE	2.38	2.47	2
Clarence River	22055.1	132.3	283001.3	2.2	WDE	BE	39.72	41.34	13
Coffs Creek	24	0.5	292.7	0.6	WDE	BE	ND	ND	3
Bellinger River	1100.3	8.2	14441.6	1.8	WDE	BE	2.45	2.55	5
Nambucca River	1298.9	12.6	23227.1	2	WDE	BE	5.24	3.96	4
Macleay River	11287	31.6	70235.2	2.6	WDE	BE	16.48	16.65	3
Hastings River	3658.6	30	52685.9	1.9	WDE	BE	21.31	19.47	8
Camden Haven	589	32.2	113802.1	3.6	WDE	BE	7.56	7.75	6
Manning River	8124.5	34.7	96258.5	3	WDE	BE	14.83	10.08	9
Wallis Lake	1196.9	98.7	217951.5	2.3	WDE	BE	13.8	16.6	5
Hunter River	21367	47	137089.4	3.3	WDE	BE	29.2	26.8	19
Lake Macquarie	604.4	114.1	646274.3	5.7	WDE	BE	11.18	10.89	8
Tuggerah Lake	714.5	80.8	193231.2	2.4	WDE	BE	ND	2.59	6
Brisbane Water	152.5	28.3	84198.7	3.1	WDE	BE	25.8	21.3	6
Hawkesbury River	21624.1	114.5	1541412	13.8	TDE	DV	191	199	14
Narrabeen Lagoon	52.4	2.3	5251.6	2.3	ICE	SCL	0.28	0.5	1
Manly Lagoon	17.2	0.1	35.6	0.4	ICE	SCL	ND	ND	1
Georges River	930.9	26.6	271393.5	10.5	TDE	DV	19.32	16.66	5
Lake Illawarra	238.4	35.8	74275.1	2.1	WDE	BE	2.14	2.7	3
Shoalhaven River	7085.8	31.9	86508.6	2.9	WDE	BE	18.35	19.03	6
Conjola Lake	139.1	6.7	26798.7	4	ICE	BE	1.47	1.75	1
Batemans Bay	28	34.5	383484.1	11.1	OE	OE	NA	NA	2
Merimbula Lake	37.9	5.6	12923.9	2.6	WDE	BE	3.27	1.86	2

WDE Wave dominated estuary
TDE Tide dominated estuary
ICE Intermittently closed estuary
OE Oceanic embayment
BE Barrier Estuary
IBE Inter-barrier estuary
DV Drowned valley
SCL Saline coastal lagoon
NA Not applicable
ND Not determined

Table 2: Details of estuaries for further assessment

Entrance	Catchment size (km^2)	Estuary area (km^2)	MHL stations	Ocean Tide Location
Coffs Creek	24	0.5	3	Coffs Harbour
Clarence River	22055.1	132.3	13	Coffs Harbour
Hunter River	21367	47	19	Port Stephens
Lake Macquarie	604.4	114.1	8	Sydney
Brisbane Water	152.5	28.3	6	Sydney
Narrabeen Lagoon	52.4	2.3	1	Sydney
Lake Illawarra	238.4	35.8	3	Sydney
Shoalhaven River	7085.8	31.9	6	Jervis Bay

Table 3: Selected ocean tide site details

Station	Classification	Primary Sensor	Station	
			Sampling	Logging
Coffs Harbour	Onshore Port	Electromagnetic	120 samples filtered each minute	1 minute
Port Stephens	Onshore Bay	Float	Instantaneous	15 minutes
Sydney	Onshore Bay	Electromagnetic	1 second samples averaged	15 minutes
Jervis Bay	Onshore Bay	Electromagnetic	1 second samples averaged	15 minutes

Figure 6: Selected estuary and ocean tide site locations

entrance conditions. The Clarence and Hunter rivers are large rivers draining directly to the ocean through well trained entrances, while the Shoalhaven River is smaller with a shoaled entrance. Coffs Creek has been included as a coastal waterway with limited estuarine storage. Catchments draining into coastal lakes of various size have been included in the form of Lake Macquarie, Brisbane Water and Lake Illawarra.

The ocean tide gauge sites selected for use were Coffs Harbour, Port Stephens, Sydney and Jervis Bay to measure ocean water levels without flood influence. The locations of the eight selected estuaries and four ocean tide gauges are shown in Figure 6. Waterway and ocean site details are listed in Tables 2 and 3.

Methodology

The Clarence River was used as a pilot waterway during the study, to refine the methodology to be adopted for subsequent waterways, as there is a long data record available with 13 water level gauges throughout the waterway and a number of large flood events on record with data going back to 1987. The locations of MHL gauging stations within the system are shown in Figure 7. Grafton was selected as the representative catchment flooding station for the Clarence River as flooding is catchment dominated but still has some tidal influence (see Figure 4). Coffs Harbour is the nearest suitable ocean tide station, as the ocean tide station in the Clarence River entrance at Yamba is influenced by flooding.

Thresholds were used to define catchment and coastal flood events and significant anomaly. Flood events at Grafton with peak levels of 1.3 m AHD and higher were correlated against peak daily ocean levels at Coffs Harbour to create the scatter plot in Figure 8. Ocean water levels at Coffs Harbour greater than 1.4 m AHD have also been included. The depicted flood level ARIs have been taken from the Lower Clarence River Flood Study (WBM, 2004). Dates in Figure 8 refer to the date of the peak flood level.

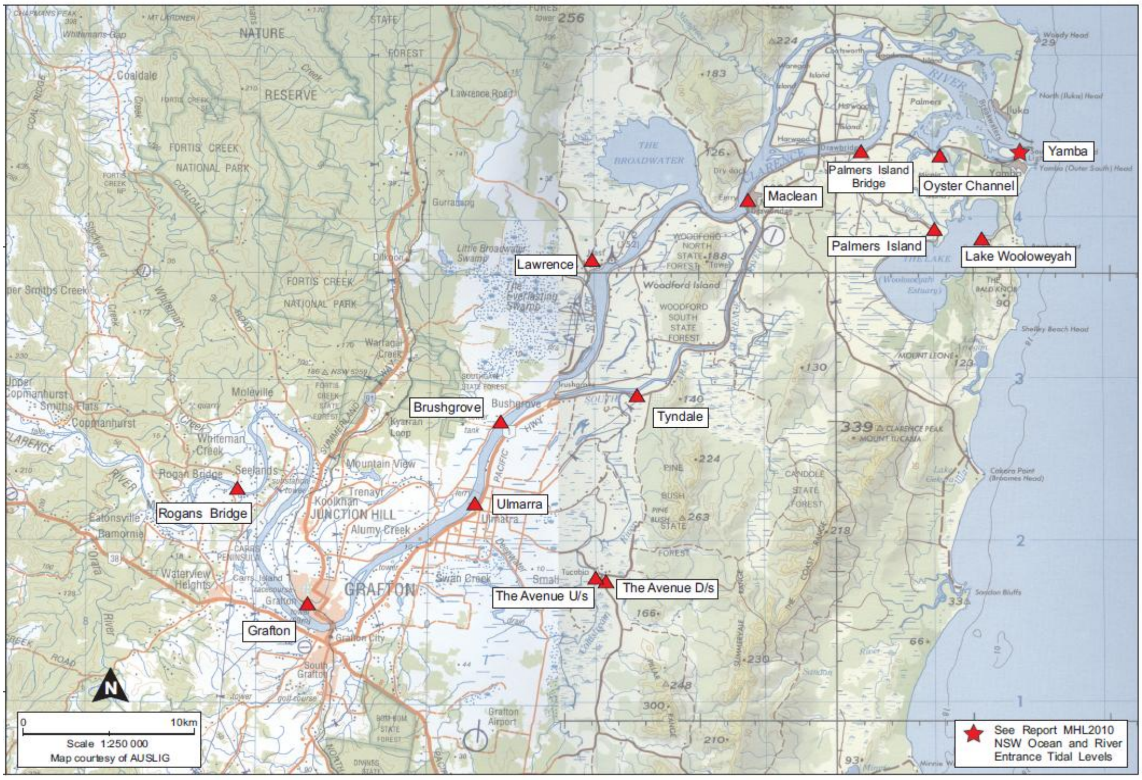

Figure 7: MHL station locations in the Clarence River

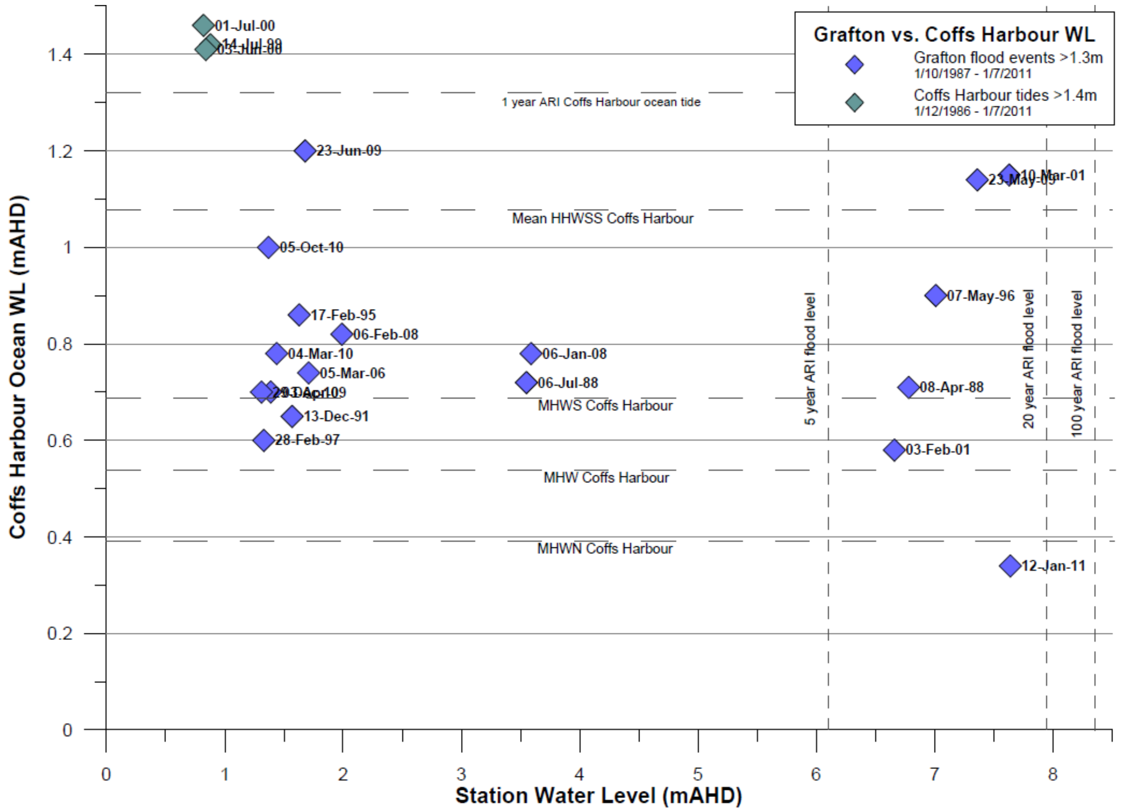

Figure 8: Grafton flood level versus Coffs Harbour ocean water level

From Figure 8 there appears to be a low level of coincidence between catchment flood event peaks in the Clarence River and elevated ocean levels. For flood events at Grafton above the 5-year ARI, the elevated ocean levels involved are all below the 1-year ARI ocean level for Coffs Harbour.

A correlation of the top 100 recorded ocean water levels at Coffs Harbour with the maximum water level at Grafton, Brushgrove and Maclean on the same day, where available, was conducted. Of these elevated ocean levels only two coincided with water levels of 1.3 m AHD or greater at Grafton.

Nine events identified from the scatter plot were selected for further investigation using time series plots, based on the size of the flood and the likelihood of coincident flood events. This included the eight largest catchment flood events and the largest ocean water level event corresponding with a flood (June 2009). Time series plots were developed to allow simultaneous visualisation of water levels at multiple waterway stations, ocean water level and anomaly, the occurrence of storm events and rainfall to track flood events down through a system, to examine the relative scale and timing of flooding at each location against elevated ocean levels, synoptic events and rainfall. For the Clarence, water levels at Grafton, Brushgrove and Maclean were included to track the floods downstream to understand the changing timing and ocean influences. Selected time-series plots including synoptic typing (easterly trough low (ETL), inland trough low (IT), anticyclone intensification (AI), tropical low (TL) and southern secondary low (SSL)), are presented in Figures 9 to 17.

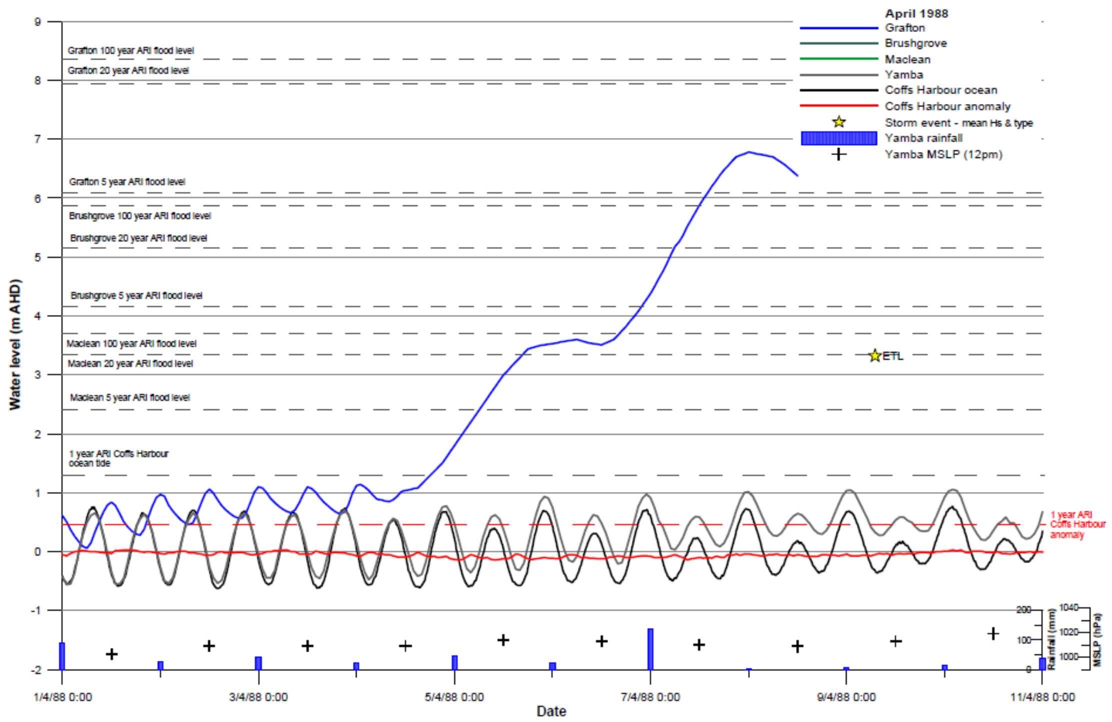

Figure 9: April 1988 flood event

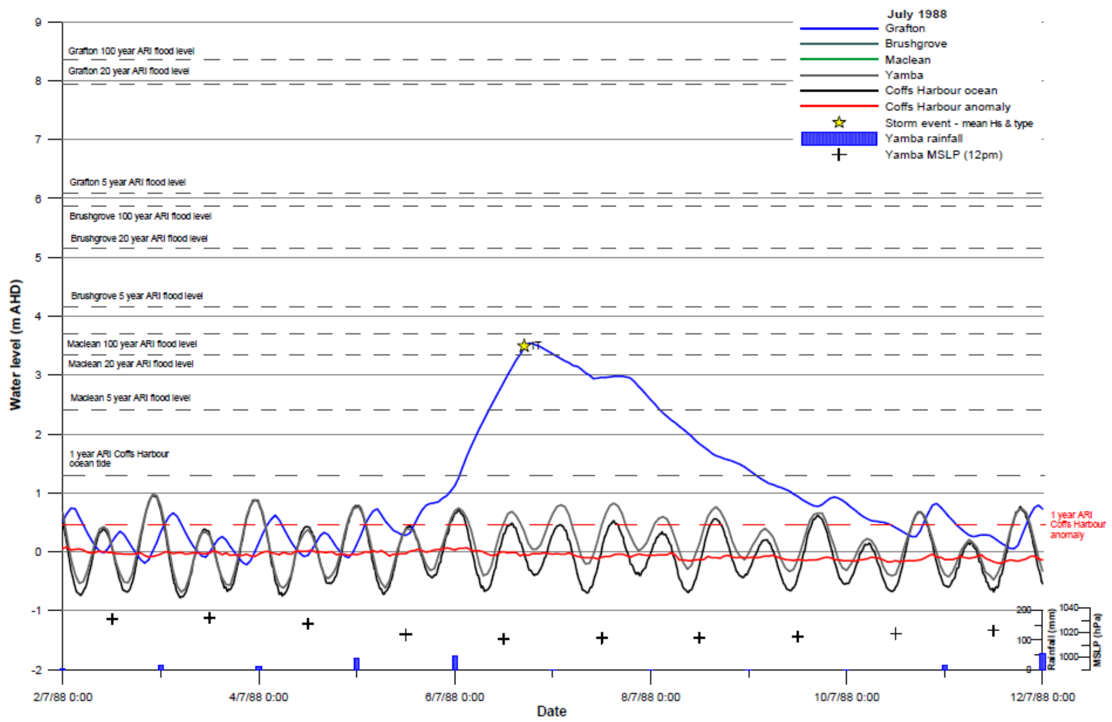

Figure 10: July 1988 flood event

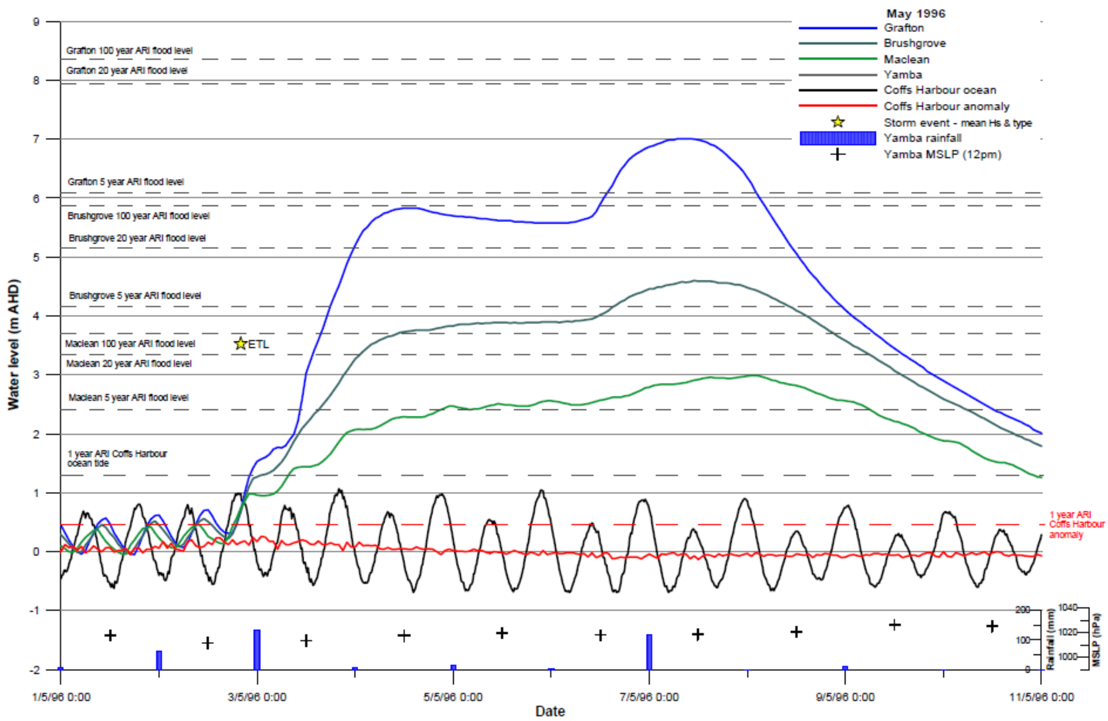

Figure 11: May 1996 flood event

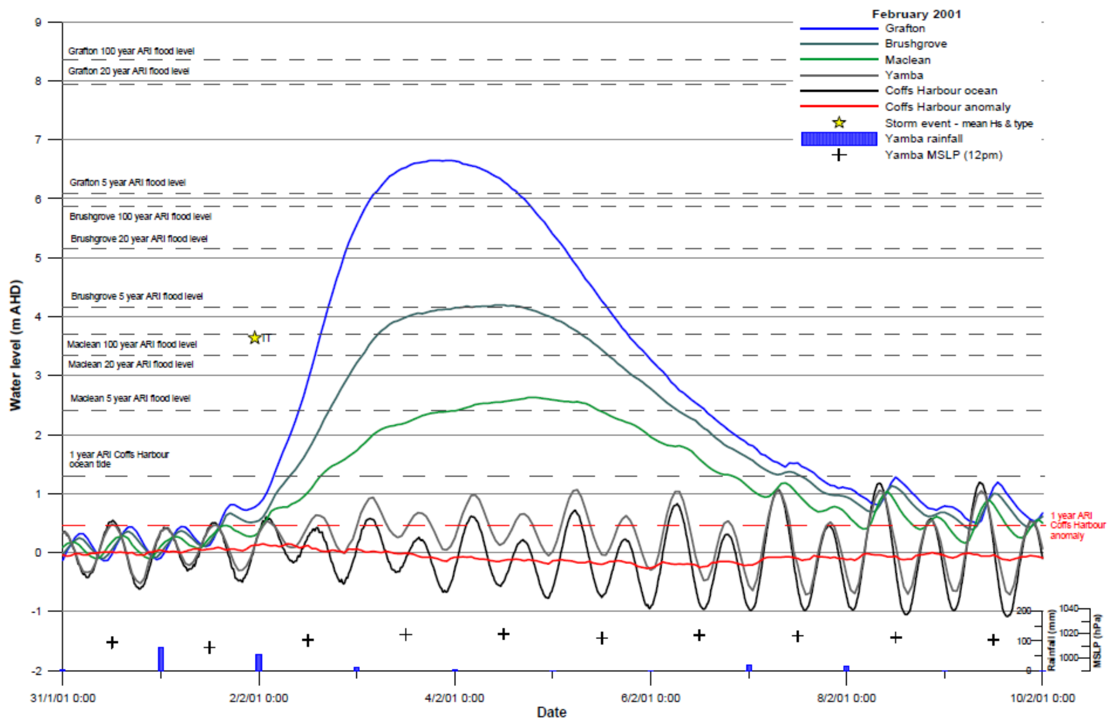

Figure 12: February 2001 flood event

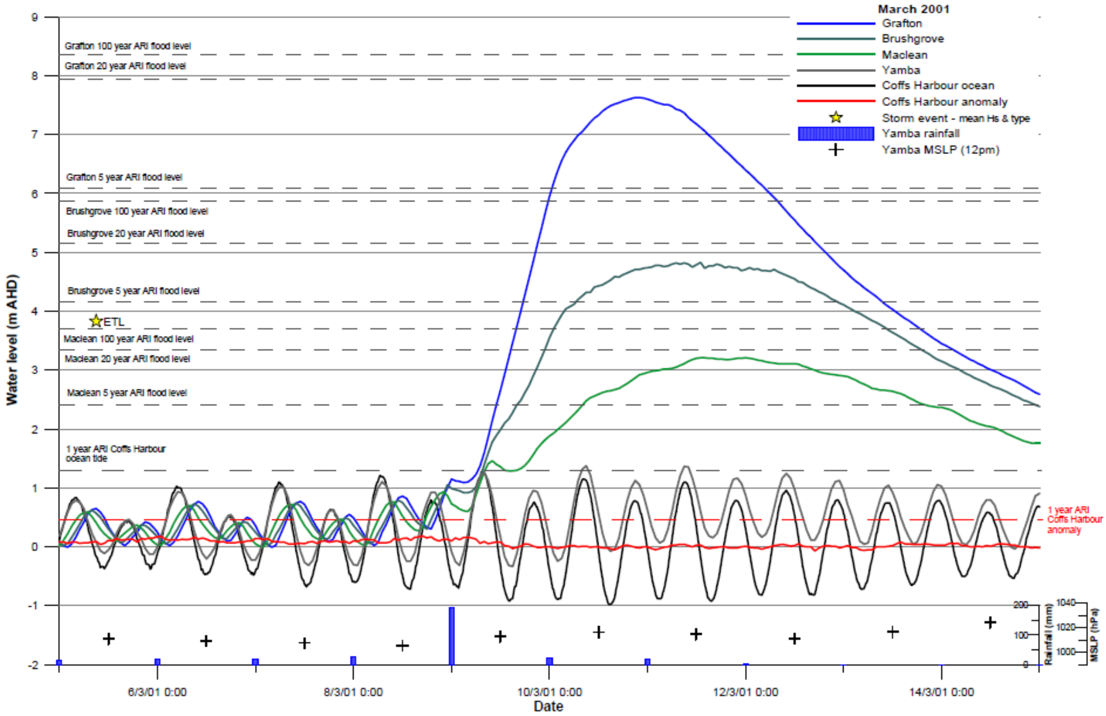

Figure 13: March 2001 flood event

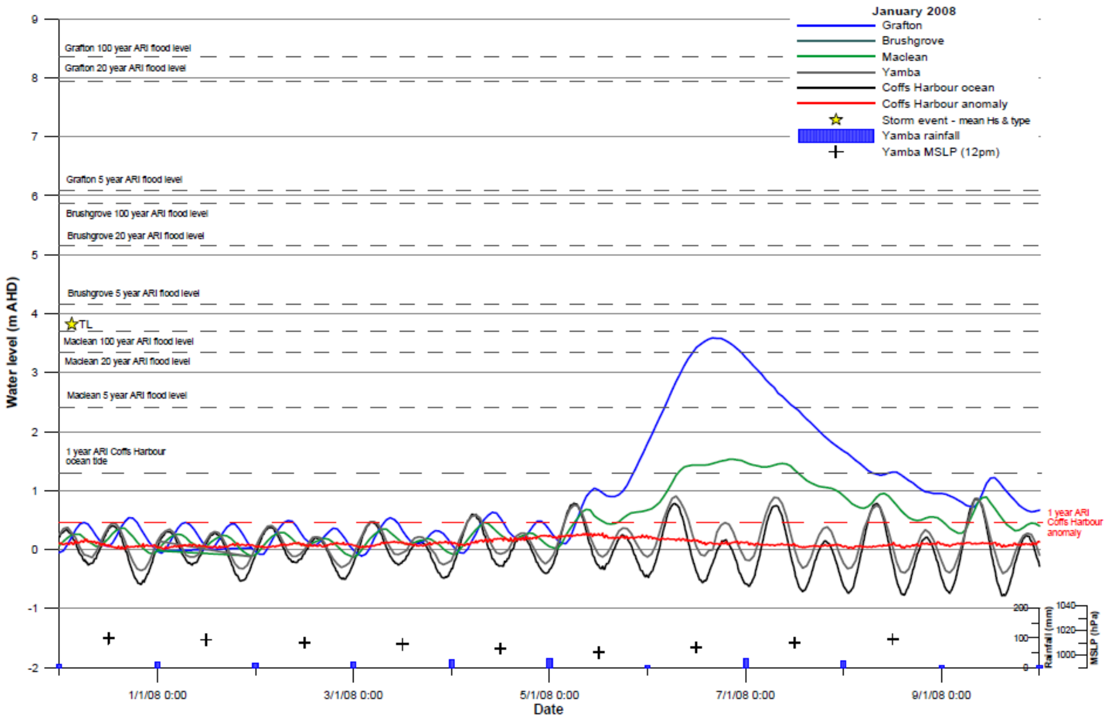

Figure 14: January 2008 flood event

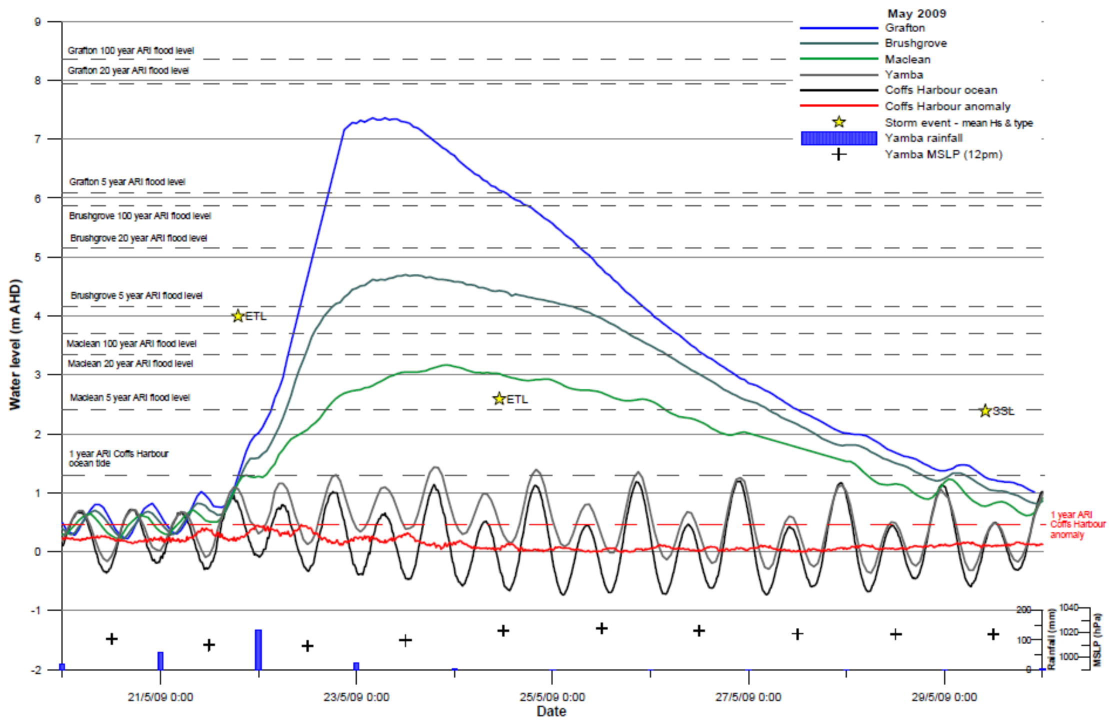

Figure 15: May 2009 flood event

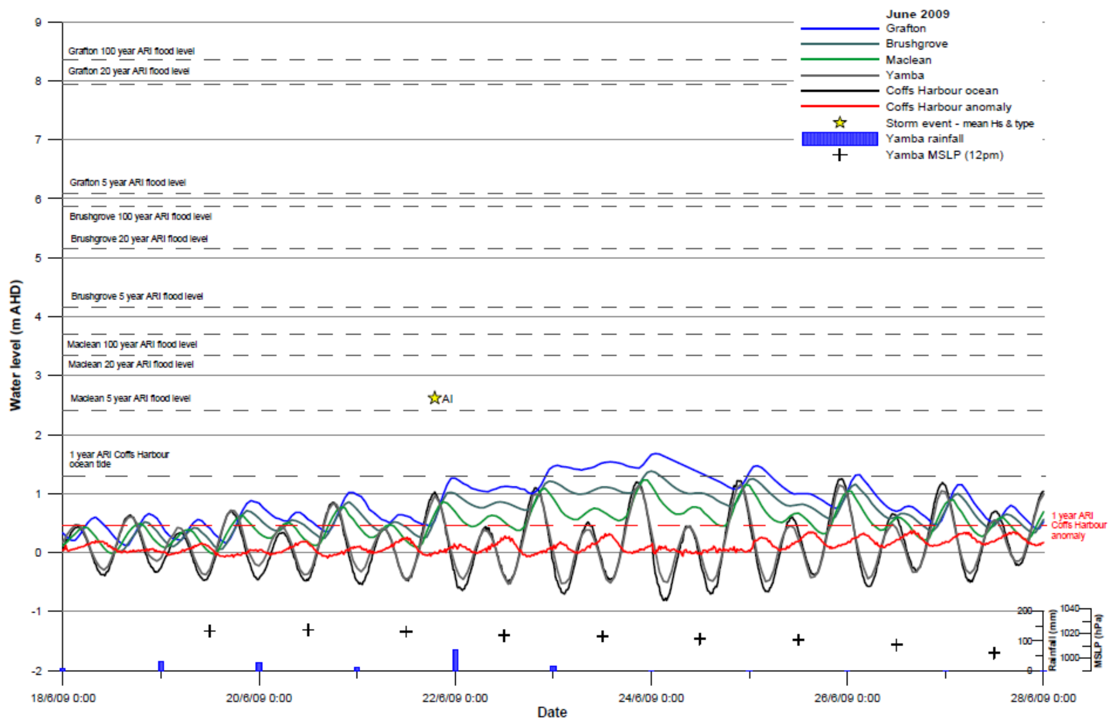

Figure 16: June 2009 event

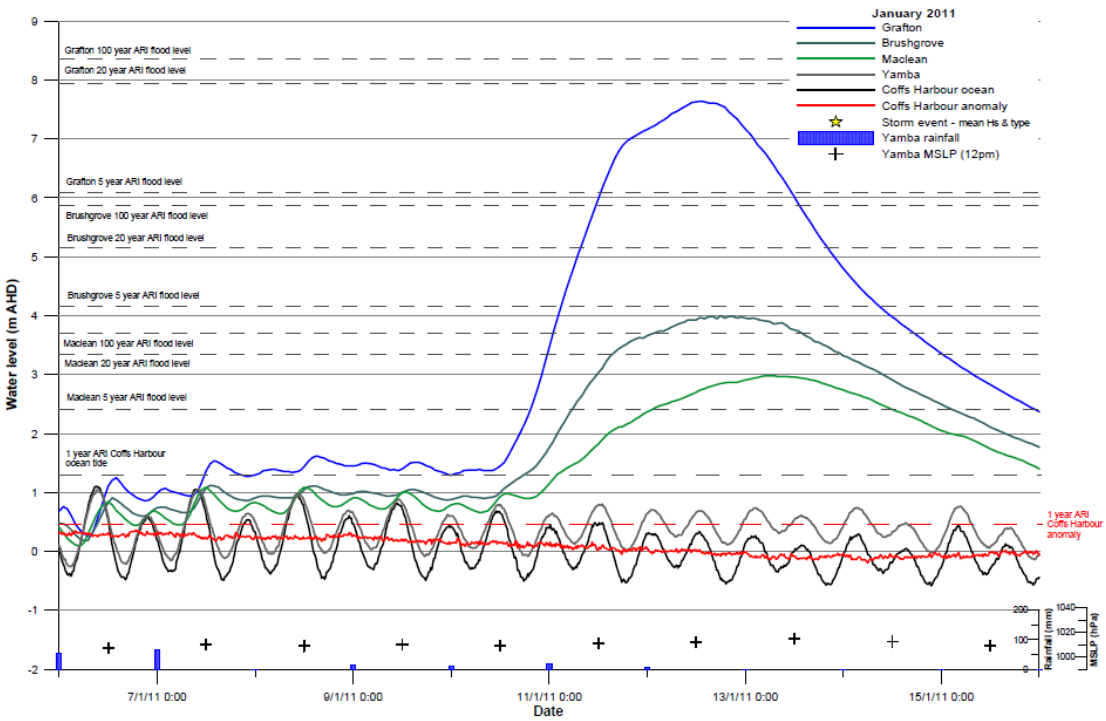

Figure 17: January 2011 flood Event

Discussion of Results for the Clarence River

Based on the above plots for the events in question, for the Clarence River at Grafton:

- There appears to be a low level of correlation between catchment flooding and elevated ocean levels (May 1996, March 2001, May 2009). Elevated ocean levels observed were below the 1-year ARI ocean water level.
- Anomalies are often present immediately before or at the beginning of a flood event (May 1996, February 2001, March 2001, January 2008, May 2009, June 2009), however the magnitudes are generally small (1-year ARI observed only during May 2009 flood) and may not coincide with a spring tide cycle (e.g. February 2001, January 2008).
- The dominant synoptic types that may be associated with flood events in the Clarence are easterly trough lows (May 1996, March 2001, May 2009) and inland trough lows (July 1988, February 2001). This is consistent with Speer et al. (2009).
- Of the top 100 recorded ocean water levels at Coffs Harbour only two coincide with floods of greater than 1.3 m AHD at Grafton (although there is missing data for some events).
- ETL, IT, TC and AI synoptic events correlating to catchment flooding in the Clarence River. However, of these only four resulted in significant ocean levels (greater than 1 m AHD) during the flood event.

Application of Methodology to Other Catchments

This methodology was then applied to the other seven selected catchments to enable the examination on other tidal waterways and different waterway type, size and location. Complications in using the methodology in other catchments that arose were:

- the need to investigate both flooding of the main lake/water body and tributary flooding for Lake Macquarie, Brisbane Water and Lake Illawarra
- the influence of entrance conditions on flooding for Narrabeen Lagoon and Lake Illawarra.

To help summarise the information developed through the analysis, Table 4, showing information regarding anomaly, peak ocean level, synoptic type and ARI for the largest 6-8 recorded catchment flood events for each analysed gauge, was developed. Table 5 shows similar details for each flood of 10-year ARI or greater (where the 10-year ARI level is not available floods considered likely to exceed the 10-year ARI have been included).

Observations from Tables 4 and 5 and further analysis of flood level versus ocean water level correlation for each waterway are summarised below:

- Of the sites chosen only Lake Illawarra, Lake Macquarie, and Coffs Creek have flood events captured above the estimated 20-year ARI, highlighting the lack of significant events in the dataset and the need to investigate sources outside of MHL's database.
- The dominant synoptic type in the events analysed was the Eastern Trough Low (ETL), especially in the Hunter and Lake Macquarie.
- Greater than 75% of the events examined had an anomaly of more than 0.1 m, with almost 10% coinciding with an anomaly greater than 0.4 m.
- The peak ocean level during catchment flood events was significantly influenced by the stage of the spring-neap cycle.
- None of the analysed floods coincided with elevated ocean levels greater than the 1-year ARI ocean level, but approximately 30% coincided with levels above the mean Highest High Water Solstice Springs (HHWSS).
- The analysed catchment floods in the Shoalhaven River had no corresponding anomalies above 0.3 m, and 50% of the events had anomalies less than 0.1 m.
- The larger lake systems such as Lake Macquarie and Brisbane Water (Koolewong) appeared to have a higher correlation to anomalies above 0.3 m than other sites chosen, while the Hunter River showed the highest correlation of the other estuaries investigated.
- Brisbane Water (at Koolewong) showed the highest correlation between flooding and high ocean levels, followed by the Hunter River. It has been found that severe ocean storms cause the highest levels within Brisbane Water rather than catchment floods of the same ARI (Cardno Lawson Treloar, 2009), and hence it is not surprising that there is high correlation between floods at Koolewong and high ocean levels and anomalies.
- Coffs Creek shows two flood events above the 20-year and 100-year ARIs which had ocean boundary condition water levels less than 1.0 m AHD.
- Lake Macquarie shows two events above the 20-year ARI which also had ocean boundary conditions less than 1.0 m AHD.
- Catchment flooding events tended to correspond with ETL and IT synoptic events, however there were a few catchment flood events that corresponded to TC, SSL and STL. SSL and STL events were observed only at Brisbane Water, Coffs Creek and Narrabeen Lagoon.

Discussion of Work to Date

This work is preliminary in nature and the drawing of and use of broad conclusions would need careful consideration. Work on this stage of the project is continuing at it will form the basis for future investigation in Stage 2. This assessment was limited by the length of the gauge data and the number of significant floods that have been observed within this period. As the storm listing by Shand et. al. (2011) is based on significant wave height it may not identify all synoptic events of interest. Drawing on this preliminary work:

- The analysis is complex because of the timing of catchment flood and ocean flood peaks, missing data, relative timing of anomalies, tidal behaviour, spatial variability of information and multiple peak floods.

Table 4: Summary of synoptic type, anomalies, flood levels and ocean levels for chosen waterways

Waterway	Gauge	# Floods analysed	# Synoptic event type							# Peak anomalies					# Peak ocean levels				# Estimated flood ARIs				
			ETL	IT	TC	SSL	STL	CL	Unknown	<0.1m	0.1-0.2m	0.2-0.3m	0.3-0.4m	>0.4m	<MHWS	MHWS-MHHWSS	MHHWSS-1yr ARI	>1yr ARI	<5 year	5 year	10 year	20 year	100 year
Clarence River	Grafton	8	4	2	-	-	-	-	2	2	2	2	1	1	1	5	2	-	2	6	ND	-	-
Coffs Creek	Coffs Creek	7	1	2	1	-	1	-	2	1	2	3	1	-	2	5	-	-	5	-	-	1	1
Hunter River	Raymond Terrace	8	5	2	1	-	-	-	-	1	3	1	2	1	-	3	5	-	ND	ND	2	-	-
Lake Macquarie	Marmong Point	8	6	1	1	-	-	-	-	-	3	1	2	2	-	5	3	-	5	1	ND	2	-
	Stockton Creek	7	5	1	1	-	-	-	-	1	3	2	1	-	1	6	-	-	ND	ND	ND	-	-
Brisbane Water	Koolewong	8	3	1	1	2	1	-	-	-	1	3	3	1	-	2	6	-	8	-	-	-	-
	Narara Creek	6	3	2	-	-	-	-	1	3	1	2	-	-	3	2	1	-	5	1	-	-	-
Narrabeen Lagoon	Narrabeen Bridge	6	1	1	-	1	-	1	2	1	1	2	1	1	-	3	3	-	ND	ND	ND	-	-
Lake Illawarra	Cudgeree Bay	8	4	3	-	-	-	-	1	3	3	-	1	1	-	5	3	-	5	2	ND	1	-
	Mullet Creek	7	2	4	-	-	-	-	1	1	4	-	1	1	1	5	1	-	7	-	-	-	-
Shoalhaven River	Nowra Bridge	8	4	4	-	-	-	-	-	4	1	3	-	-	1	6	1	-	ND	ND	1	-	-

ND - Not determined

Table 5: Summary of synoptic type, anomalies, flood levels and ocean levels for flood events above 10 year ARI

Estuary	Gauge	Flood event	Synoptic type	Peak anomaly (m)	Peak ocean tide (mAHD)	Peak flood level (mAHD)	Estimated flood ARI levels (mAHD)					
							5 year	10 year	20 year	50 year	100 year	200 year
Clarence River	Grafton	Jan-11	Unknown	0.31	0.69	**7.64**	6.1	ND	7.95	8.36	8.42	ND
		Mar-01	ETL	0.18	1.29	**7.63**	6.1	ND	7.95	8.36	8.42	ND
		May-09	ETL	0.45	1.02	**7.36**	6.1	ND	7.95	8.36	8.42	ND
Coffs Creek	Coffs Creek	Mar-09	TC	0.24	0.99	**5.11**	3.76	ND	4.3	ND	4.8	5.2
		Nov-09	STL	0.05	0.87	**4.42**	3.76	ND	4.3	ND	4.8	5.2
Hunter River	Raymond Terrace	Feb-90	TC	0.36	0.95	**3.01**	ND	2.7	3.2	3.7	4.6	ND
		Oct-85	IT	0.14	0.89	**2.86**	ND	2.7	3.2	3.7	4.6	ND
Lake Macquarie	Marmong Point	Jun-07	ETL	0.25	0.93	**1.1**	0.65	0.8	0.97	1.24	1.38	1.55
		Feb-90	TC	0.37	0.94	**1**	0.65	0.8	0.97	1.24	1.38	1.55
	Stockton Creek	Jun-07	ETL	0.25	0.93	**2.54**	ND	ND	2.78	3.07	3.31	ND
Brisbane Water	Narara Creek	Jun-07	ETL	0.25	0.93	**3.51**	ND	ND	ND	4.1	4.6	ND
	Koolewong	Jun-07	ETL	0.25	0.93	1.11	1.35	1.43	1.51	1.6	1.68	1.77
Lake Illawarra	Cudgeree Bay	Jun-91	ETL	0.03	1.04	**1.8***	1.4	1.55	1.8	2	2.3	ND
	Mullet Creek	Jun-91	ETL	0.03	1.04	3.3	4.65	4.84	5.07	5.33	5.55	ND

Flood level exceeds ARI

Flood level may exceed ARI, no data available for comparison

*No MHL data available - level taken from flood study

ND - No data

- Where the catchment and coastal flooding are both being driven by the same synoptic type there is a higher likelihood for coincidence.
- Tidal anomaly heights are reasonably consistent across NSW, with a slight trend for higher anomalies to the north (MHL, 2011a). This study did not show a tendency for greater correlation between catchment flooding and ocean anomaly in northern NSW, with the greatest correlation occurring at the Hunter River, Lake Macquarie and Brisbane Water.
- The coincidence of coastal and catchment flooding varies with waterway type.
- The type of entrance will influence the impact of the timing of the anomaly. For example, a waterway with a large lake at the entrance such as Lake Macquarie will be influenced greater by an anomaly of a few days duration prior to the flood because of the pumping effect it has on the lake level and the time it takes for the anomaly to extend into the lake, whereas Coffs Creek will be greater impacted by an anomaly directly before a flood event because of its immediate influence.

Recommended Further work

Stage 2 of this project and subsequent research is necessary to expand upon Stage 1 and will seek to:

- Examine earlier flood events such as the major storm of May 1974, where sufficient data exists on both catchment flooding events and coastal storm events to assess their coincidence.
- Determine key factors for coincidence of events in different tidal waterways.
- Examine other sources to improve knowledge of storm type for correlation.
- Consider coincidence based upon dominant storm types resulting in catchment and coastal flooding.
- Investigate other sources for flood data including various flood studies to be included into the data sets for analysis.
- Consider other key factors that can increase or decrease the likelihood for coincidence.
- Undertake modelling work to examine the influence of the timing of anomalies and tidal boundary conditions on flooding. For example early anomalies will reduce available flood storage, while just prior to the flood peak it will reduce the ability of water to drain from the system. The influence of this timing will be dependent on entrance type.

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