PRELIMINARY EXAMINATION OF COASTAL AND CATCHMENT FLOODING INTERACTION FROM THE DATA

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Abstract

The interaction of coastal and catchment flooding is an important consideration in determining flood risk and subsequent planning and management measures in estuarine environments. The influence of flooding from each of these sources, and their combination, on overall flood risk varies with distance upstream from the ocean and various estuary characteristics.

This paper examines the occurrence of joint coastal and catchment flooding events from data records for a number of different estuary types in NSW. It presents the results of a study of continuous water level data records from the ocean up to the tidal limit of eight selected estuaries. The estuaries were chosen based upon entrance, waterway and catchment characteristics, geographic location and availability of recorded data. Water level data was interrogated to investigate the relative timing and magnitude of ocean levels, ocean anomalies and estuary levels during significant flood events. The information derived was then analysed to determine the historical occurrence of, and likely influences on, the coincidence of elevated ocean conditions and catchment flooding.

A number of potential trends regarding the effect of various estuary characteristics on the historical level of coincidence between catchment driven flooding and large ocean anomalies were identified. There are, however, limitations to observations and relationships derived from the study, and further investigation is required. The outcomes of the study are intended to contribute toward further work which may lead to the update of practical policy on the treatment of ocean tailwater conditions in flood planning.

Introduction

Flooding in tidal waterways can be the result of catchment flooding, elevated ocean conditions or a combination of the two. Coastal conditions can significantly impact flooding in the lower reaches of tidal waterways via their influence on water level gradient and rate of discharge to the ocean, and / or the filling of available storage within the waterway prior to catchment flooding. The interaction of catchment and coastal flooding is complex and its significance may depend on a range of factors including: catchment shape, size and location; waterway characteristics including entrance type, storage configuration and system response time; the likelihood of a meteorological event resulting in both catchment driven flooding and elevated ocean levels (there may be similarities or differences in the drivers responsible for each); the relative timing of the peaks of these events; and the location and relative vulnerability of infrastructure and communities.

To improve understanding of these issues and their relevance in particular cases, the NSW Office of Environment and Heritage (OEH) was successful in obtaining funding under 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).

This paper is based on work undertaken for OEH by NSW Public Works' Manly Hydraulics Laboratory (MHL), to provide a preliminary assessment of what can be derived from available NSW water level gauge data in regard to the historical occurrence of coincident coastal and catchment flooding events. The NSW coastal water level database used for this study includes in excess of 20 years of continuous water level data for most of the coastal rivers, estuaries and lakes in NSW (typically since at least 1990) as well as ocean levels recorded along the NSW coast.

The work undertaken will provide input and direction for further study that may lead to an ability to develop improved guidance on the consideration of the interaction of coastal and catchment flooding in flood planning.

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

- drivers for elevated ocean conditions and how these may relate to synoptic types and storm events likely to cause catchment flooding
- current advice on the coincidence of coastal and catchment flooding in flood planning, and on the influence of coastal conditions on tidal waterways.

Drivers for Ocean Conditions Likely to Influence Flooding in Tidal Waterways

Appropriate selection of tailwater conditions at the ocean entrance is important when defining flood risk in tidal waterways. Factors requiring consideration include astronomical tide; various contributors to ocean anomaly; the effects of waves within estuary entrances; the likelihood of joint occurrence of elevated ocean entrance water levels and catchment flooding; the potential importance of event durations and system response time; and the influence of ocean entrance characteristics on the translation and impact of ocean conditions in the waterway.

Tides along the NSW coast are semi-diurnal with a significant diurnal inequality. Tidal range varies along the coast with an increase of around 0.2 m from south to north as shown in Figure 1 (MHL, 2011).

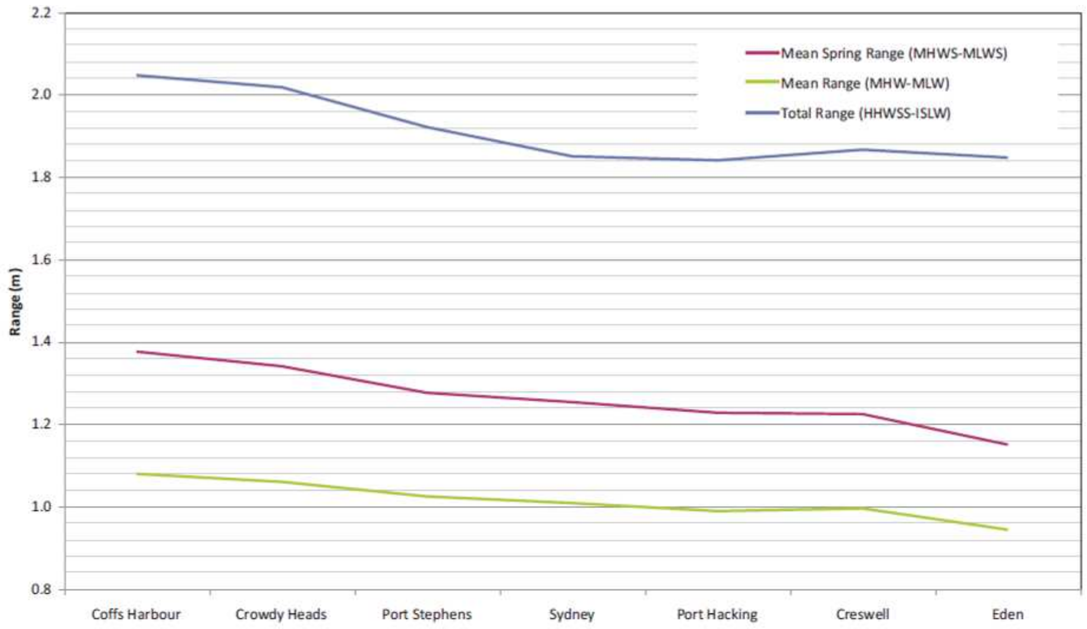

Figure 1: NSW tide ranges (Source: MHL 2011)

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. Annual anomalies are reasonably consistent along the NSW coast, with a slight trend for higher anomalies toward the north (MHL, 2011). Drivers of tidal anomalies include variations in air pressure and wind stress - the combined effects of which, during storms, are 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, 2011). These oscillations can see variation in annual mean sea level of around 10 cm.

At higher frequencies many factors contribute to anomalies but the largest contributors are typically storm surge and coastal trapped waves. Coastal trapped waves propagate south to north with wave heights of around 20-30 cm and can elevate coastal water levels for several days (Church et al. 1986a, b; MHL, 2011). Storm surge along the NSW coast can raise water levels by over 50 cm (e.g. NSW Government, 1990), and can be fairly short-lived or last for more prolonged periods (days) depending on storm characteristics and propagation. 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 estuary entrances water depth and entrance morphology play a significant role in modifying tidal behaviour and effects are likely to vary significantly between different waterway types. In large coastal lakes for example, entrance constriction and shoaling results in rapid attenuation of the tidal range (e.g. Figure 2). 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 as, or larger than, the semi-diurnal tide. Similarly, water levels in coastal lakes would be expected to be more affected by longer duration ocean anomaly events.

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.

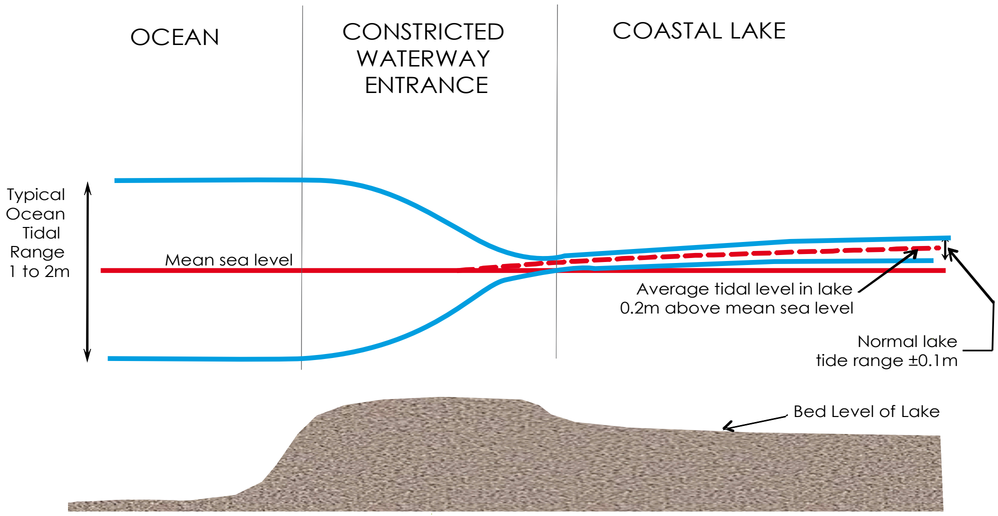

Figure 2: Example of Entrance Impact on Tidal Ranges in an Open Coastal Lake with a Constricted Entrance (Souce: McLuckie et al. 2010)

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, 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 NSW Government 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. 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.

To determine conditions relevant for flood planning for the 1% AEP (or 100-year ARI) flood in coastal waterways, NSW Government advice recommends, in lieu of a site specific assessment, 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 3 provides a simplistic illustration of these events.

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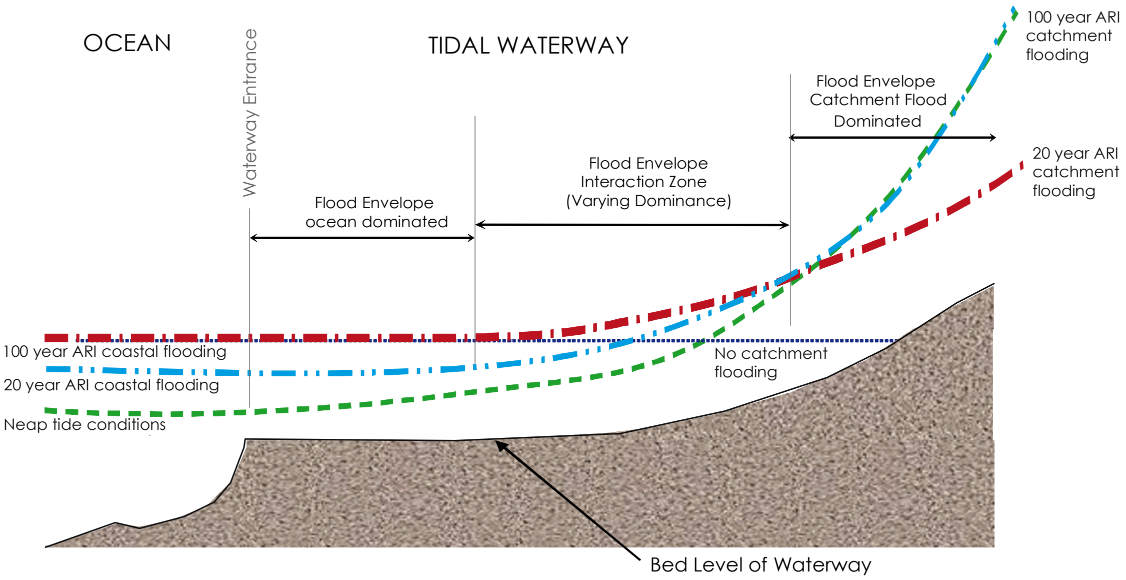

Figure 3: Interaction of catchment and coastal flooding (Souce: McLuckie et al. 2010)

The work from the current project, and any subsequent studies, is likely to enable a review of the above approach 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 current advice, work has recently been undertaken on Australian Rainfall and Runoff Revision Project 18: Interaction of Coastal Processes and Severe Weather Events (Westra 2012). This work involves statistical extreme value analysis of the degree of "joint dependence" between rainfall and tidal anomaly - that is the relative level of occurrence of meteorological events associated with both rainfall and a rise in ocean level - based upon available national datasets. Preliminary findings indicate that the level of dependence between rainfall and tidal anomaly is heavily influenced by the duration of rainfall event, with dependence increasing with duration. Whilst this work improves understanding of coincidence, the following points need be considered:

- The significance of catchment flooding resulting from rainfall 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.

- Statistical analysis has been carried out on rainfall and tidal anomaly data sets over a limited period of record with only few statistically large flood events included. Whilst noting the need to include a sufficiently large sample size in the analysis to limit uncertainty, it may be that the degree of joint dependence observed varies with the severity of rainfall event investigated. Considering this, and their significance in terms of floodplain risk assessment, threshold rainfall and anomaly levels adopted may be relatively low. Complicating this further is the importance of the duration over which the rainfall has fallen.
- Depending upon the characteristics of a given estuary, the importance of the timing and duration of a tidal anomaly relative to flooding arising from rainfall may vary.

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.

Data Sources

Estuary Water Level Data

MHL maintains an extensive water level database for the NSW coast that has been developed to support a number of OEH programs associated with floodplain, coastal and estuary management. At the time of writing, the MHL/OEH environmental data recording network consists of 250 estuary and river water level gauges, 23 ocean tide gauges (refer below), 7 ocean wave buoys and 80 rainfall gauges. The water level gauges cover all NSW coastal basins including 107 rivers, creeks, lakes and lagoons, with over 30 years of data at some sites. The NSW coastal database served as the primary source of information used in the study, covering the period of record up to 1 July 2011.

Ocean Level and Anomaly Data

The 23 ocean tide stations managed by MHL on behalf of OEH are located on the NSW coast between Tweed Heads and Eden, and cover a range of sites including offshore, river, estuarine, ports and open bays. Onshore open ocean and open bay gauges that are unaffected by flood events provide the most reliable long-term trend and anomaly analysis and were therefore the only ocean gauges considered for use in this report.

The tidal anomaly data series used in this study have been calculated by subtracting predicted tides from recorded water levels, where predicted tides have been calculated using harmonic analysis after Foreman (1977).

MHL Tidal Data Reports

The results of tidal analysis carried out for NSW Ocean Water Levels (MHL 2011) and the draft report NSW Tidal Planes Analysis 1990-2010: Stage 1 Harmonic Analysis (MHL 2012) were utilised to give context to the relative significance of ocean levels and anomalies.

Estuary Characteristics

Data on physical characteristics of each NSW estuary within MHL's water level data network was compiled from the OEH webpage *Estuaries of NSW: Physical characteristics, tidal surveys and hydrographic surveys* (http://www.environment.nsw.gov.au/estuaries/list.htm). This data was used to ensure that estuaries of a range of types and sizes were considered in the study.

Synoptic Type Data

To identify the synoptic storm type associated with identified flood events in the study, NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves (Shand et al. 2011) was utilised. The report contains a storm history table listing 1078 storms detected by wave buoys based on peak significant wave heights (Hs) of 3 m and over between 1971 and 2009.

This data set has limitations for the purpose of this study in that storms causing catchment flooding and / or ocean anomaly may not cause large wave heights and vice versa. Furthermore, the reported storms and their date are based on the peak significant wave height (Hs) recorded at any NSW wave buoy and, therefore, may not affect the specific waterway being investigated or may affect the waterway on a different date to that reported. Additionally, the storm listing does not cover the full period of investigation. Analysis of synoptic typing has, therefore, been limited in this study.

Flood Studies

Flood studies for each of the waterways to be investigated in detail were sought to provide design flood levels to give a relative context to the size of the recorded floods within the data record.

Rainfall and Mean Sea Level Pressure Data

Daily rainfall and mean sea level pressure (MSLP) data was sought from the Bureau of Meteorology (BoM) for inclusion in time-series data analysis of flood events.

Estuary Selection and Data Examination

Selection of Study Estuaries

Eight estuaries were selected for investigation based on the availability of suitable data records, and with an aim to cover a range of estuary and entrance types spread geographically along the NSW coast. The wish to include estuaries spread from north to south along the coast was tempered by the need to analyse suitably long periods of water level data with a number of significant floods on record. It was found that many waterways do not have multiple large floods on record, and that the occurrence of large floods has been somewhat skewed toward the north during the period of MHL water level records that extend primarily since the early 1990s.

The vast majority of estuaries in NSW are wave-dominated barrier estuaries (54) and intermittently closed estuaries (110) (Roy et al. 2001). Only one intermittent estuary, Narrabeen Lagoon, was assessed, as the periods of water level record available were relatively short and the magnitude of flooding in such estuaries is often dominated by the condition of the entrance. The remaining seven selected sites were wave-dominated barrier estuaries spread geographically along the NSW coast and with varying size and 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 sizes have been included in the form of Lake Macquarie, Brisbane Water and Lake Illawarra. Creeks flowing into these lakes were also included.

The ocean tide gauge sites selected for use were Coffs Harbour, Port Stephens, Sydney and Jervis Bay due to their proximity to the selected estuaries and their independence from flood influence. Waterway and ocean site details are listed in Tables 1 and 2. The locations of the eight selected estuaries and four ocean tide gauges are shown in Figure 4.

Table 1 Selected Study Estuary Details

Estuary	Catchment size (km^2)	Estuary area (km^2)	MHL stations	*Start of record	Ocean tide location
Clarence River	22055.1	132.3	13	Jul-87	Coffs Harbour
Coffs Creek	24	0.5	3	May-73	Coffs Harbour
Hunter River	21367	47	19	Apr-80	Port Stephens
Lake Macquarie	604.4	114.1	8	May-86	Sydney
Brisbane Water	152.5	28.3	6	Aug-85	Sydney
Narrabeen Lagoon	52.4	2.3	2	Aug-86	Sydney
Lake Illawarra	238.4	35.8	3	Dec-87	Sydney
Shoalhaven River	7085.8	31.9	6	Jan-90	Jervis Bay

*Start date of longest station record in waterway

Table 2 Selected Ocean Tide Site Details

Station	Period of data collected	Classification	Primary sensor	Station	
				Sampling	Logging
Coffs Harbour	1987-present	Onshore Port	Electromagnetic	120 samples filtered each minute	1 minute
Port Stephens	1985-present	Onshore Bay	Float	Instantaneous	15 minutes
Sydney	1987-present	Onshore Bay	Electromagnetic	1 second samples averaged	15 minutes
Jervis Bay	1989-present	Onshore Bay	Electromagnetic	1 second samples averaged	15 minutes

Figure 4 Selected Estuary and Ocean Tide Site Locations

Detailed Data Examination

For each of the eight selected estuaries a key water level site was selected to represent catchment flooding. For the lakes studied an additional site was also selected, where available, to investigate tributary creek flooding. The study aimed to investigate ocean conditions coinciding with catchment floods, not to assess the impact of observed ocean levels on flood levels at any location. The key stations were therefore used only as an indicator of the occurrence of catchment flooding, and flooding at the station need not be strongly influenced by ocean levels (for example Grafton).

Estuary flood levels above approximately a 1-year recurrence interval at the key sites were extracted and correlated against peak ocean level and peak ocean anomaly on the same day. Similarly, ocean levels and ocean anomalies exceeding 1-year ARI levels were correlated against peak estuary water level on the same day. While noting that higher ocean levels and anomalies may have occurred on different dates during or prior to the flood event, this data gave a preliminary indication of the level of coincidence between catchment flooding and elevated ocean conditions in the study estuaries and helped to identify events for further investigation.

Given the variation in flood durations (between events and estuaries), and the differing importance between estuary types of the timing of elevated ocean conditions in relation to flooding, automated correlation and statistical analysis of coincidence would need to be undertaken with great care and a degree of manual checking. Visual assessment of time-series data for flood events was, therefore, considered appropriate to derive relevant peak ocean levels and anomalies coinciding with a flood. In general, several of the largest recorded flood events in each study estuary, along with other identified events of interest, were plotted as time-series. Information on synoptic event type, peak ocean levels, peak ocean anomalies and their timing relative to flooding was then tabulated from these plots.

Results and Discussion

This work is preliminary in nature and the drawing of and use of broad conclusions beyond its aims of informing future research is not recommended. 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. The identification of synoptic events is limited to those determined in the storm listing by Shand et al. (2011), which was based on significant wave height.

Analysis of Significant Flood Events

Floodplain management in NSW is generally most concerned with less frequent events such as the 100-year ARI flood and rarer floods, with the 5-year ARI flood typically being the smallest event of interest. Ideally this study would limit analysis to floods of such magnitudes, however, given the comparatively short periods of water level data sets in existence (20 to 30 years) few large floods were found on record. A total of 13 flood events exceeding (or considered likely to be exceeding) estimated 10-year ARI levels were found, with only six of the eight study estuaries represented. A summary of these events is presented in Table 3.

Table 3 Data Summary for Floods Exceeding 10 year ARI

Estuary	Station	Flood event	Synoptic type#	Peak ocean anomaly (m AHD)	Peak ocean level (m AHD)	Peak flood level (m AHD)	Estimated flood ARI levels (m AHD)					
							5 year	10 year	20 year	50 year	100 year	200 year
Clarence River	Grafton	Jan-11	Not listed	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	Nov-96	TC	0.27	0.96	**5.2***	3.76	ND	4.3	ND	4.8	5.2
		Mar-09	TC	0.26	0.99	**5.11**	3.76	ND	4.3	ND	4.8	5.2
		Nov-09	STL	0.07	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	0.38	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
Lake Illawarra	Cudgeree Bay	Jun-91	ETL	0.04	1.03	**1.8***	1.4	1.55	1.8	2	2.3	ND

	Anomaly exceeds 1-year ARI level
	Flood level exceeds ARI
ND	Flood level may exceed ARI, no data available for comparison

*No MHL data available - level taken from flood study
Source: Shand et al. 2011
ETL - Easterly Trough Low
IT - Inland Trough Low
TC - Tropical Cyclone

In general, for these events there is some level of coincidence evident between flooding and moderate ocean anomalies, however only one flood event above the 10-year ARI coincided with an anomaly exceeding the 1-year ARI magnitude. Easterly trough lows and tropical cyclones were the dominant synoptic types that appear to be associated with floods above a 10-year ARI magnitude. Observed peak anomalies during tropical cyclone flood events were consistently moderate to high (range 0.26-0.38 m) but did not exceed the 1-year ARI, while peak anomalies during easterly trough low events ranged widely (0.04-0.45 m), with one event exceeding the 1-year ARI anomaly.

Comparison of Ocean Anomaly and Ocean Level Analysis

Whilst noting the limitations of this preliminary assessment, results of the study show the apparent level of coincidence between catchment flooding and elevated ocean levels (above the 1-year ARI) is relatively low. Given the range of ocean anomalies observed in the events analysed for this study (maximum observed anomaly of 0.45 m), it was found that the spring-neap cycle and tidal phase had the greatest impact on total ocean levels occurring during catchment floods.

The tide coinciding with a flood event is a function of independent astronomical factors that are unrelated to catchment flooding and is therefore theoretically random. Certain contributors to ocean anomalies (such as storm surge) can, however, be linked to meteorological events that cause catchment flooding, while other independent contributors have varying probabilities of occurrence. It may, therefore, not be surprising that a higher level of coincidence between catchment flooding and large ocean anomalies (exceeding the 1-year ARI) was found. While several floods coincided with moderately high ocean levels of greater than 1 m AHD, only one event coincided with an elevated ocean level in excess of the 1-year ARI. This event occurred at Brisbane Water and did not coincide with significant catchment rainfall.

In the case of Brisbane Water the comparatively high level of coincidence between flooding and elevated ocean conditions is explained by relatively strong tidal forcing compared with catchment inputs, where some recorded events (such as April 1990 and 2 June 2000) appear to have been driven by elevated ocean conditions alone without the occurrence of catchment rainfall. Indeed, Cardno Lawson Treloar (2009) found that water levels in Brisbane Water for a given ARI were higher for ocean-driven flooding than catchment-driven flooding.

For the purposes of this study, analysis of the correlation between catchment flooding and ocean anomalies provided greater value in assessing the coincidence of catchment and coastal flooding. Analysis has not discriminated between the various contributors to ocean anomalies, whose coincidence with rainfall may be linked or independent, and thus all have been included in a probabilistic context.

Analysis of Coincidence Levels and Relative Timing

To allow a comparison of the apparent level of coincidence of catchment flooding and coastal flooding in each estuary to be carried out, it was necessary to include in analyses several of the largest floods recorded in each estuary. The fraction of flood events, out of those analysed, that coincided with elevated ocean levels exceeding the relevant 1-year ARI; coincided with large ocean anomalies exceeding the relevant 1-year ARI; and, coincided strongly with the timing of an ocean anomaly, is presented in Table 4.

Table 4 Summary of coincidence levels

Estuary	Station	Number of events with coincidence between flooding and elevated ocean levels (>1-yr ARI)	Number of events with coincidence between flooding and large ocean anomalies (>1-yr ARI)	Number of events with coincidence between timing of flooding and ocean anomalies
Clarence River	Grafton	0/8	1/8	2/8
Coffs Creek	Coffs Creek	0/8	0/8	4/8
Hunter River	Raymond Terrace	0/10	1/10	4/10
Lake Macquarie	Marmong Point	0/8	2/8	5/8
	Stockton Creek	0/7	0/7[1]	2/7
Brisbane Water	Koolewong	1/8	2/8	6/8
	Narara Creek	0/6	0/6	1/6
Narrabeen Lagoon	Narrabeen Bridge	0/7	2/7	5/7
Lake Illawarra	Cudgeree Bay	0/9	1/9	2/9
	Mullet Creek	0/7	1/7	1/7
Shoalhaven River	Nowra Bridge	0/7	0/7	2/7

[1]One event was within 2 mm of the 1-year ARI level

In general, it was found that there is some level of coincidence between catchment flooding and large ocean anomalies evident. In the majority of the estuaries and tributaries studied at least one of the analysed floods coincided with an ocean anomaly exceeding the 1-year ARI. Some level of coincidence between the timing of catchment floods and ocean anomalies was also evident, with at least one of the analysed floods at each analysed monitoring station strongly coinciding with the timing of an ocean anomaly.

The analysed coastal lakes (Lake Macquarie, Brisbane Water and Lake Illawarra) and coastal lagoon (Narrabeen Lagoon) generally showed the highest level of coincidence between flooding and large ocean anomalies, and the strongest coincidence between the timing of floods and ocean anomalies. Lake Illawarra exhibited a lower level of coincidence than the other analysed lakes. While flooding in Brisbane Water is ocean dominated (Cardno Lawson Treloar 2009), all but one of the analysed flood events involved at least some rainfall.

The analysed river systems (Clarence, Hunter and Shoalhaven rivers) generally showed a lower level of coincidence between flooding and large ocean anomalies, and a lower coincidence between the timing of floods and ocean anomalies, than the coastal lakes. Coincidence levels observed for the Shoalhaven River were particularly low.

The small coastal creek (Coffs Creek) and lake tributary creeks (Stockton, Narara and Mullet creeks) generally showed little coincidence with large ocean anomalies, and variable levels of coincidence between the timing of floods and ocean anomalies. It is notable that flood levels in these creeks are responsive to relatively short durations of high intensity rainfall.

Discussion of Factors Influencing Coincidence of Flooding and Ocean Anomaly

Based upon analysis of the above results, and consideration of various estuary characteristics, a number of likely influences on the coincidence of estuarine flooding and ocean anomaly have been identified. The importance of each influence is difficult to determine as multiple factors contribute to any given result.

Possible factors influencing observed levels of coincidence include:

- *Estuary type* – As may be expected, differences in coincidence levels were found between different estuary types (i.e. rivers, lakes, lagoons and creeks). Significant variation was, however, observed between estuaries of the same type, and many other factors, therefore, require consideration.
- *Responsiveness of estuary water levels to differing intensities and durations of rainfall* – Significant differences in coincidence levels were observed between catchments where water levels are sensitive to high intensity short duration rainfall (e.g. Coffs Creek and lake tributary creeks) and those more affected by high volumes of rain falling over a longer duration (e.g. large river systems and coastal lakes). This behaviour is influenced by characteristics such as catchment size, waterway area and storage configuration, as well as entrance conditions. The results suggest that meteorological events responsible for flooding in catchments with quick response times are less likely to be associated with the occurrence of large ocean anomalies. This observation is supported by the findings of Westra (2012). Several flood events within the lake tributary creeks were, however, found to coincide with flooding of the main lake body. This highlights the potential for short bursts of high intensity rainfall to occur within longer duration events.
- *Location of catchment areas in relation to the coast* – The catchment areas of large river systems extend much further inland than those of other estuary types and are affected by inland rainfall. The coincidence with elevated coastal conditions of meteorological events causing significant inland rainfall and those resulting in only coastal rainfall are likely to differ. Differences in coincidence levels between analysed river systems and coastal systems (i.e. coastal creeks, lakes and lagoons) were observed, however, results were influenced by numerous factors.
- *Impact of ocean conditions on estuary water levels relative to catchment flows* – the significance of ocean conditions on overall flood levels is determined by estuary characteristics including catchment size, waterway surface area and entrance conditions. The significance of ocean level to overall flood levels is generally greater in estuaries with a low catchment size to waterway area ratio, with waterway area relative to entrance flow conditions also an important factor. With the exception of Lake Illawarra, the estuaries with the lowest catchment area to waterway surface area (Lake Macquarie, Brisbane Water and Narrabeen Lagoon) exhibited the highest coincidence between flooding and large ocean anomalies of those analysed. This may be expected as, due to low catchment inflows, high flood levels are less likely to be reached in these estuaries (particularly Brisbane Water) without the presence of elevated ocean conditions. In the case of Lake Illawarra, the ocean entrance has historically been highly constrained, meaning responsiveness of lake levels to ocean conditions was low, and high flood levels have generally been related to entrance closure. Entrance works and dredging were completed in 2007, since when the entrance has remained open to the ocean. It would be expected that, under the present conditions, Lake Illawarra would experience similar levels of coincidence as other coastal lakes. Similarly, the entrance to Narrabeen Lagoon is subject to significant shoaling, however an open entrance has generally been maintained by routine dredging over the period of MHL records.

- *Geographic location (latitude)* – Based on the limited flood data and number of estuaries analysed, it is difficult to draw conclusions on the role of geographic location, from north to south, in observed levels of coincidence. Results show some indication of a lower coincidence between catchment flooding and large ocean anomalies on the south coast, however, it is likely that this observation is heavily influenced by other important factors including a lower occurrence of significant floods in the south during the period of records.

Conclusions and Recommendations

This work is preliminary in nature and the drawing of and use of broad conclusions beyond its aims of informing future research is not recommended. Despite their growing value and importance, the length of water level records used for this study are limited in terms of capturing a statistically significant number of major flood events. Furthermore, relative quantification of coincidence levels and comparisons between estuaries are complicated by the variation in water level records available for each estuary in terms of the differing length of record; number of floods on record; and magnitudes of floods on record. The significance of observed trends is also difficult to determine due to the possible influence of multiple unrelated factors. Any observations and conclusions derived from the preliminary analysis are thus not considered to be definitive, and require further investigation.

Analysis of water level data records indicates that there is some level of coincidence between catchment flooding and large ocean anomalies (exceeding the 1-year ARI) along the NSW coast, while coincidence with elevated ocean levels (exceeding the 1-year ARI) was found to be very low. Given that the spring-neap cycle and tidal phase greatly impact total ocean levels coinciding with a flood event, and are a function of unrelated astronomical factors, the study found greater value in analysing the correlation between catchment flooding and ocean anomalies.

While there were exceptions, coastal lakes and lagoons were generally found to exhibit the highest level of coincidence between flooding and large ocean anomalies, followed by large river systems, with small coastal creeks having the lowest level of coincidence. Observed levels of coincidence appear to be higher where:

- estuary water levels are responsive to high volumes of rain falling over a longer duration, rather than intense short duration rainfall
- ocean conditions have a significant impact on estuary water levels relative to catchment flows.

The behaviour of an estuary in respect to these influences on coincidence depends primarily upon estuary characteristics including catchment size, waterway area and configuration, and ocean entrance condition in terms of flow capacity.

A number of avenues for further study into the coincidence of coastal and catchment flooding have been identified as a result of the current study. These include:

- Application of similar methodologies to additional estuaries, with an aim to further investigate whether the potential trends identified by this study are reflected in the behaviours found at other estuaries. This may be achieved through case studies that specifically target particular estuary characteristics while eliminating other variables. Investigation of additional estuaries would also allow the influence of various estuary characteristics to be better examined.

- The investigation of additional historical flood level data from flood studies and other sources in order to increase the number of major floods available for analysis. This exercise may be limited to estuaries within a justifiable distance from Sydney, as the Fort Denison record is likely to be the only ocean level data available for correlation. The available historic records may limit this potential.
- Further investigation of specific meteorological events including their influence on water levels in various affected estuaries, synoptic typing, key drivers contributing to observed ocean anomaly and if these share any link to the occurrence of catchment flooding mechanisms, as well as analysis of rainfall and anomaly event durations and their relative timing.

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