Reducing Public Safety Risk at a NSW Breakwater

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Observations, photographs, physical modelling and empirical calculations indicate that wave overtopping events pose a very high threat to the safety of pedestrians and vehicles that use the Coffs Harbour North Breakwater crest. Research, based on the application of industry recognised science to site specific conditions and analysis of data (measured, observed and anecdotal), was conducted to inform the development of a Action Plan to reduce the risk to the public from wave overtopping. This Plan is consistent with Crown Lands' risk management framework.

The objective of the research undertaken to date was to establish appropriate trigger(s) (based on predicted and real time measured ocean conditions) that defines when risk to the public accessing the breakwater is considered unacceptable. Paramount to the Plan was development of criteria that generally allowed for continued access to the North Breakwater and Muttonbird Island Nature Reserve, while reducing risk levels to the public during hazardous conditions. The trigger criteria are used for the initiation of precautionary actions as outlined below.

The Plan contains several phases and associated actions and responsibilities, e.g:

- Pre-planning and pre-event phase - including monitoring metocean conditions through real time data, the Bureau of Meteorology (BoM) web site and other public domain web based forecasting sites

- Stand-by phase - when trigger levels are forecast to be exceeded (this includes when the Bureau of Meteorology (BoM) issues a Severe Weather Warning for dangerous waves or storm surge)

- Implementation phase - when trigger levels are expected to be exceeded. Measures include visual warning signage, evacuating people from Muttonbird Island and closing public access to the breakwater

- Post-event phase - inspections to ensure the area is safe, prior to re-opening public access

The methodology could be applied to other coastal structures where overtopping places the public at risk.

INTRODUCTION

Public access to the Coffs Harbour North Breakwater crest during periods when waves are overtopping the structure represents a significant public safety risk and raises public liability concerns for the NSW Crown Land Division (referred to here after as Crown Lands).

Crown Lands is the asset owner of the breakwater and is responsible for management of the breakwater. In order to reduce the risk, Crown Lands have initiated investigations and the preparation of a Risk Management Plan (RMP) for the north breakwater. The RMP provides a framework for evacuation procedures including required actions and organisational responsibilities.

This paper outlines investigations undertaken to define and evaluate the definition of appropriate trigger level(s) when public access to the breakwater should be restricted. A summary of the recommended procedures for the closure and evacuation of pedestrians from the breakwater and Muttonbird Island also provided.

COFFS HARBOUR NORTH BREAKWATER

Coffs Harbour is situated approximately half way between Sydney and Brisbane on the NSW mid-north coast. Constructed between 1914 and 1946, the port of Coffs Harbour consists of two outer harbour breakwaters and two inner harbour breakwaters (Figure 1). The inner harbour is widely considered to provide the safest anchorage between Port Stephens and Moreton Bay. It currently provides shelter for a commercial fishing fleet and a recreational boating marina.

Figure 1: Layout of port of Coffs Harbour

The north breakwater connects Muttonbird Island to the mainland and is heavily used by pedestrians to access marina berths and Muttonbird Island and for general recreation (walking, jogging, fishing etc).

Muttonbird Island Nature Reserve provides the opportunity to observe a wedge-tailed shearwater (mutton bird) rookery and is a popular vantage point to view the annual whale migration. The NSW National Parks & Wildlife Service (NPWS) estimates that the island attracts more than 100,000 people each year. Tourism is a major regional industry contributing approximately $300 million annually to the local economy (Coffs Harbour City Council's Economic Development Unit, 2011).

BREAKWATER OVERTOPPING

The section of the Coffs Harbour North Breakwater most susceptible to overtopping is between the 2^{nd} and 5^{th} marina finger wharfs, on the eastern section of the breakwater (Figure 2). The crest level along this section is approximately 5.0 m AHD and has a crest pavement width of just under 4 m. On the ocean side large (8 to 20 tonne) concrete armour units are above the level of the pavement. On the harbour (or marina) side a hand rail separates the crest pavement from the rock slope. A series of stairs, provide access to the marina finger wharfs.

Stormy conditions characterise the weather during the majority of wave overtopping events. These weather conditions would generally be expected to reduce the numbers of recreational pedestrians using the breakwater. However, the 'sceptical' of wave overtopping attracts spectators and 'thrill seeker', who intentionally place themselves at risk. Pedestrians are also known to access the breakwater even in the most severe events (Figure 3). Overtopping events can also occur during fine conditions when large long-period swell waves occur from NE - E.

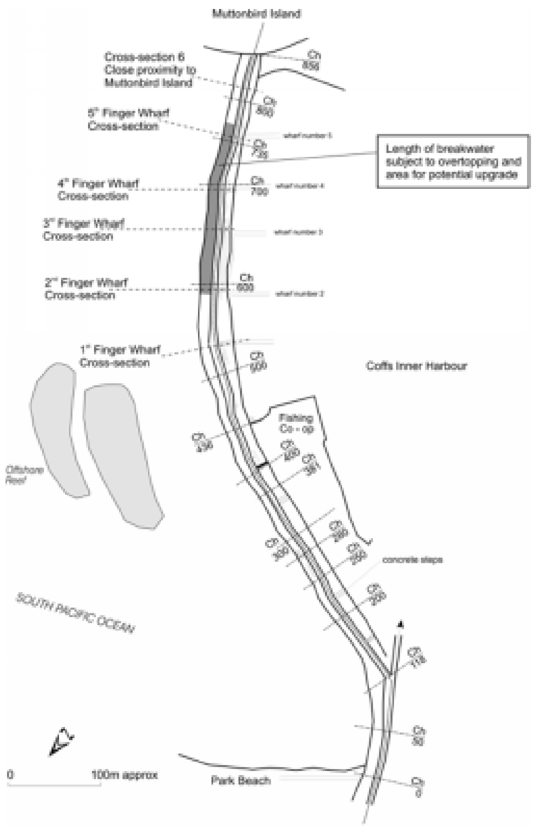

Figure 2: Coffs Harbour North Breakwater showing section subject to wave overtopping (sourced from MHL, 1994)

Figure 3: Observed pedestrian behavior during wave overtopping events. Top two images show crowds (left) and ‘thrill seekers’ (right) for the event of the 30 December 2007. Bottom two images show a pedestrian crossing during a severe event in May 1999 (image source: *The Coffs Coast Advocate* - North Coast News Pty Ltd.)

RISK MANAGEMENT FRAMEWORK

The risk management process and risk matrix depicted in Figure 4 form the basis of the risk management framework generally implemented by Crown Lands.

The trigger levels defined in the RMP aim to achieve a risk to pedestrians accessing the Coffs Harbour North Breakwater in the low range.

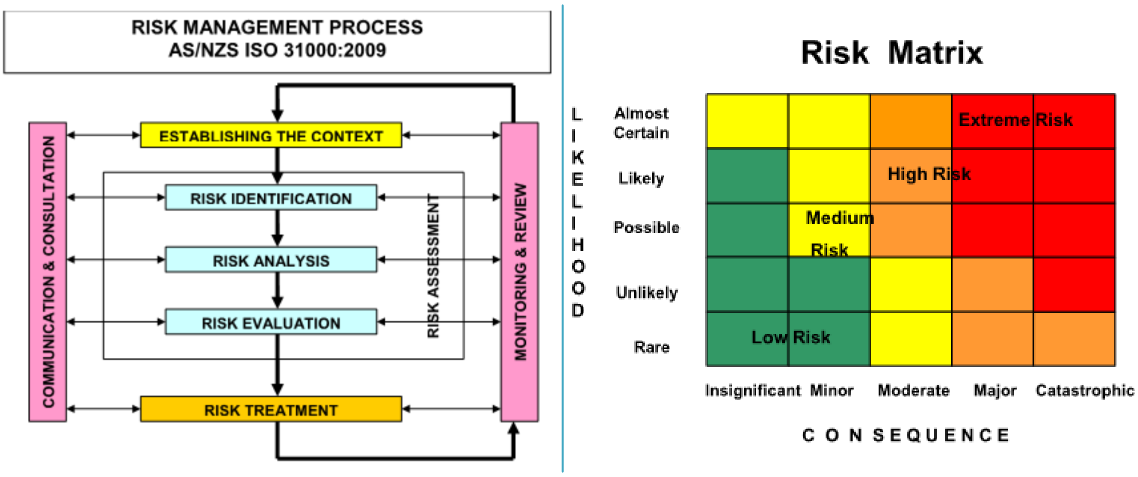

Figure 4: Reproduced from Crown Lands risk management guidelines

CATEGORISATION OF HAZARD

Wave overtopping can range from a nuisance to a threat to life. The three principal processes by which wave overtopping can occur are described below in the order of increasing hazard:

- **Spray**: strong wind can blow water onshore from the crest of nearshore waves.
- **Splash**: when waves crash against the slope of the coastal defence, water can splash onto the crest. These droplets (or falling jets when splash is more intense) are generally propelled toward the breakwater crest (or well over and

beyond the crest for heavy droplets) due to the momentum imparted to them by the breaking wave and the slope of the structure. Steep and breaking waves hitting the defence are more likely to cause overtopping by this process than surging waves (which do not have steep faces).

- **Wave run-up**: when waves meet a coastal defence (e.g. breakwater), the conservation of energy and momentum leads to the water running-up the face of the defence. If there is enough momentum in the wave run-up to pass over the crest of the defence, then significant discharge of water over the crest can occur. This defines the 'green water' case, where a continuous sheet of water passes over the crest. Surging waves are more likely to cause this type of overtopping than plunging waves, as plunging waves break before reaching the defence resulting in a considerable reduction in wave height. At higher still water levels, freeboard decreases. As such, wave overtopping is more likely to be severe during high water level periods.

The hazard to pedestrians during severe overtopping events, when wave run-up leads to 'green water' flows over the crest, is relatively clear. However, defining the threshold when the combination of these processes becomes unsafe for pedestrians is difficult. Limited guidance on this is given in the available literature.

Figure 5 presents the critical mean overtopping discharges used for design of seawalls CIRIA/CUR (1991). It can be inferred that a mean overtopping discharge value of 0.004 l/s/m is considered a low risk to pedestrians, while mean overtopping discharge values greater 0.03 l/s/m are considered dangerous.

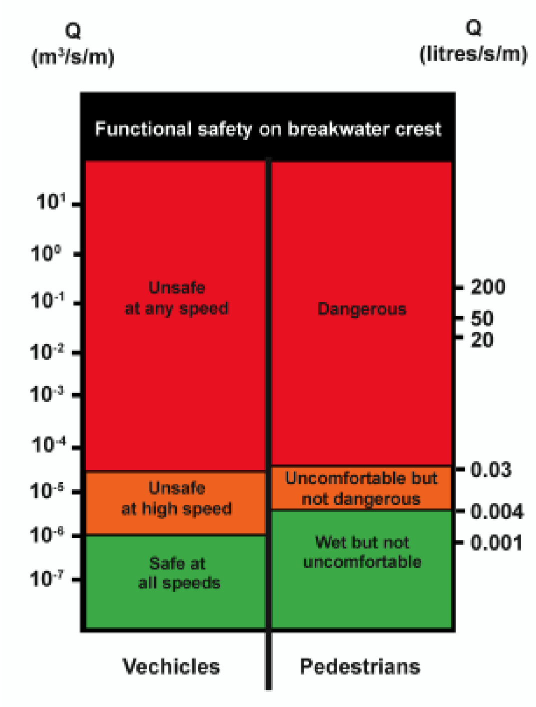

Figure 5: Critical mean overtopping discharges (adapted from CIRIA/CUR (1991))

The '*EurOtop Wave Overtopping of Sea Defences and Related Structures: Assessment Manual'* (EAUK, 2007) is generally considered to be the most comprehensive guideline available for assessment of wave overtopping. It provides tolerable overtopping criteria for pedestrian access as shown in Table 1. These thresholds are based on the analysis of wave overtopping perceived by port engineers to be safe (Goda *et al.* 1975 and Fukuda *et al.* 1974)

Table 1: Overtopping limits for trained and aware pedestrians (source: EAUK, 2007)

Hazard description	Mean overtopping discharge Q (l/s/m)	Max volume[1] V_{max} (l/m)
Trained staff - well shod and protected, expecting to get wet, overtopping flows at low levels only, no falling jet, low danger of fall from walkway.	1-10	500 at low velocities
Aware pedestrian - clear view of the sea, not easily upset or frightened, able to tolerate getting wet, structure has wide walkway.	0.1	20-50 at high velocities

Note[1]: These limits relate to overtopping velocities well below $v_c \approx 10$ m/s. Lower volumes may be applicable if the overtopping process is violent and/or overtopping velocities are higher.

The EurOtop manual notes that tests on the effects of overtopping on people, based on mean overtopping discharges alone may not be a reliable indicator of safety in some circumstances, and that maximum individual volumes may be better indicators. The manual also states a further precautionary limit of 0.03L/s/m might also apply for conditions where pedestrians have no clear view of the sea.

In addition to the inconsistencies described above, there is no evidence to suggest that these tolerable/critical mean discharge guidelines have been applied to the management of public safety on breakwater crests due to wave overtopping.

In the absence of site-specific guidance on functional safety is available for the Coffs Harbour North Breakwater, a mean overtopping discharge of 0.1 l/s/m was adopted in this study, after EAUK (2007).

DEFINING TRIGGER LEVELS

Paramount to the success of the RMP is the definition of appropriate trigger criteria that adequately reduces risk during hazardous conditions, while allowing continued public access to Coffs Harbour North Breakwater and Muttonbird Island at other times. Trigger criteria define the metocean conditions that are likely to cause dangerous overtopping at the breakwater.

The trigger criteria would be used to assist Crown Lands in the initiation of precautionary actions (e.g. evacuation and closure of the breakwater). As such, the metocean parameters used to define the trigger criteria need to be readily available in marine forecasts and real-time data sets and be simple and non-ambiguous (i.e. wave height).

Given the difficulty in defining the thresholds of safe pedestrian conditions for the Coffs Harbour North Breakwater a number of independent approaches to defining trigger values were undertaken. These were:

- engineering calculations, including empirical overtopping equations and site-specific physical and numerical modelling

- combination of anecdotal evidence and historical recurrence intervals of overtopping conditions

- combination of photographic records of overtopping events and real-time records of metocean conditions

This approach was aimed at gaining a better understanding of site specific mean overtopping discharge values in relation to observed crest overtopping conditions (and hence public safety).

Trigger levels based on engineering calculations

Empirical equations are available to calculate the significant wave height (H_{mo}) at the toe of the breakwater for a given mean overtopping discharge (per metre of structure width). For the purposes of this investigation, a simple armoured slope equation for safety assessment was used (EAUK, 2007):

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot exp\left(-2.3 \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right) \cdot 1000 \qquad \text{Eqn (1)}$$

where:

q =	mean overtopping discharge per metre of structure width	[l/s/m]
g =	acceleration due to gravity	[m/s^2]
H_{m0} =	estimate of significant wave height H_s from spectral analysis	[m]
R_c =	crest freeboard of structure	[m]
γ_f =	Correction factor for permeability and roughness	-
γ_β =	Correction factor for oblique wave attack	-

For the adopted safety threshold value of 0.1 l/s/m, the significant wave height trigger at the toe was determined using *Equation 1* to be 1.8 m for a still water level of 1.3 m and breakwater crest height of 5 m AHD.

Physical modelling of wave overtopping at Coffs Harbour North Breakwater has previously been undertaken by the Manly Hydraulic Laboratory as reported in MHL (2004). Using a simplified structural dimension with a crest height of 5 m and slope of 1:1.4, wave overtopping tests were conducted at a still water level of 1.3 m AHD. The physical model testing indicated that a significant wave height of 2.2 m at the toe would generate 0.1 l/m/s of overtopping discharge.

Considering that the still water level adopted is above Highest Astronomical Tide (HAT) at the site (1.2 m AHD), the modelled results are conservative in nature which is consistent with the objectives of the RMP.

Based on the above, significant wave height triggers at the toe would range from **1.8 to 2.2 m.**

While wave heights at the toe of the Coffs Harbour North Breakwater are not readily available in marine forecasts or real-time data sets, offshore wave conditions are. The NSW Office of Environment and Heritage (OEH) operates a non-directional wave rider buoy which is located 12 km due east of the port of Coffs Harbour in 75 to 80 metres of water.

In order to provide offshore parameters, wave transformation modelling was undertaken to hindcast wave transformation coefficients at the site. These coefficients allow for wave conditions at the toe of the breakwater to be converted to an offshore equivalent.

Numerical wave transformation modelling was undertaken for an offshore significant wave height of 5 m and peak wave period of 12 s, and for wave directions from the NE, ENE, E and ESE sectors. These directions were selected as a previous report by MHL (2010) indicated that extensive wave overtopping was associated with waves from ENE to ESE directions.

Based on the model simulations, the wave transformation coefficients at the toe of the breakwater ranged from 0.43 to 0.51, relative to offshore wave height. A wave transformation coefficient of 0.5 was therefore adopted for the purposes of estimating wave height trigger levels for these wave directions. The associated offshore significant wave height would therefore range from **3.6 to 4.4 m**, based on the threshold values at the toe of the breakwater.

Following this initial analysis, additional numerical wave transformation modelling was undertaken for an offshore significant wave height of 5 m and peak wave period of 12 s, and for wave directions from the SE, SSE, and S sectors. These directions were modelled as a high proportion of larger storm waves occur from these sectors and at extreme wave heights may cause dangerous conditions at the breakwater, despite significant wave diffraction/refraction.

Based on the additional model simulations, the wave transformation coefficients for each offshore direction at the toe of the breakwater are:

- South East: 0.42
- South South East: 0.37
- South: 0.34

Accordingly, based on the trigger levels at the toe of the breakwater, the associated offshore significant wave height for each offshore wave direction would range from:

- South East: **4.3 to 5.2 m**
- South South East: **4.9 to 5.9 m**
- South: **5.3 to 6.5 m**

Preliminary sensitivity testing of the effect of wave period on the modelled transformation coefficients was undertaken. As wave height at the toe of the breakwater is used for calculating overtopping discharge rates, consideration was made of whether shoaling of long period waves (significantly >12 sec) would increase wave transformation coefficients, hence lowering offshore wave height trigger levels.

This is of particular importance in considering waves from the NE quadrant which may be of low wave height and very long wave period (swell from distant cyclone systems in the Coral Sea).

The preliminary analysis indicated that for wave periods of greater than 14 s, shoaling of wave heights from the NE quadrant may become significant enough to reduce offshore wave height trigger levels. On this basis, it was considered conservative to reduce wave height trigger levels by 0.5 m for wave periods exceeding 14 s.

Trigger levels based on anecdotal information and historical records

Incidences of significant wave overtopping at the Coffs Harbour North Breakwater is well-known to the local community. Anecdotal evidence pertaining to the observed frequency of these events was sought. This included:

- review of previous literature
- telephone discussion with local staff based at the harbour

- consultation with relevant stakeholders

A review of the limited available anecdotal evidence suggested that dangerous wave overtopping conditions at the Coffs Harbour North Breakwater are observed approximately one to three times per year[1]. Due to the subjective nature of such evidence and the possibility of dangerous conditions not being 'observed' due to the timing of such events (e.g. at night time, or two storms in close succession being considered as one event) a value of **six times per year** was adopted to include a 100% factor of safety. This conservative approach is consistent with the objectives of the RMP.

Based on approximately 17 years (1993 – 2009) of wave height measurements from the Coffs Harbour waverider buoy (MHL, 2010a) and hindcast[2] direction estimates (for all storms measured with H_S > 3 m), MHL, 2010a prepared a joint occurrence table, which is reproduced in Table 2.

[1] Information collected from Coffs coast guard base commander adjacent to breakwater, local water police officer who is frequently called out to remove 'thrill seekers' and anecdotal evidence reported in Coastal Processes in Coffs Harbour Region (Carley *et al.* 2006).
[2] Wave hindcasting involves estimating wind direction and hence wave direction from synoptic charts.

Table 2: Coffs Harbour storm directional distribution

Peak H_s	Average number of storms per year from different directions 1993-2009								Average. no. storms/yr
	S	**SSE**	**SE**	**ESE**	**E**	**ENE**	**NE**	**ENE**	
3.0	5.58	3.84	2.89	1.57	1.41	0.54	0.21		15.99
3.5	3.35	2.31	1.65	0.91	0.83	0.41	0.08		9.54
4.0	1.61	1.03	0.95	0.7	0.5	0.25	0.04		5.07
4.5	0.54	0.41	0.54	0.41	0.25	0.04			2.19
5.0	0.25	0.25	0.41	0.29	0.17	0.04			1.38
5.5	0.12	0.17	0.25	0.08	0.12				0.69
6.0	0.04	0.04	0.12	0.08	0.04				0.3
6.5		0.04	0.08	0.04					0.13
7.0			0.04						0.04
Total storms	**135**	**93**	**70**	**38**	**34**	**13**	**5**	**0**	

It can be seen that storms with significant wave heights greater than 3, 3.5 and 4 m for waves from NE to ESE directions occurred approximately nine, five and three times per year respectively between 1993 to 2009.

Considering the relative magnitude of offshore wave heights from all directions (S to NE) which have been indicated as producing dangerous conditions based on empirical and modelling techniques, the following H_{mo} trigger level regime has been derived to account for the adopted **6 times per year** criteria:

- 3.5 m for directions NE to E;
- 4.0 m for ESE
- 4.5 m for SE
- 5.5m for SSE
- 6.0 m for S

This approximates the lower end of the range of wave heights for NE to SE directions and the median of the range of wave heights for more southerly directions, derived from engineering calculations.

The mid-range wave heights for the more southerly directions are considered conservative due to the empirical calculations (Equation 1) being based on wave approaching normal to the breakwater structure. For the more southerly offshore directions waves approach the breakwater at an oblique angle due to refraction processes thus reducing wave run-up and overtopping.

Conservative values have been selected to maintain consistency with the risk management framework.

Trigger levels based on photographed overtopping events

Time-stamped images for a range of overtopping events were sourced from Crown Lands, Coffs Harbour Marina, the local newspapers (*The Coffs Coast Advocate*) and from photos taken during site visits.

Metocean conditions during the periods in which the images were captured were derived from near-by metocean stations, as listed below:

- OEH Coffs Harbour waverider buoy - significant wave height and peak period
- OEH Sydney and Byron waverider buoys - wave direction
- Bureau of Meteorology (BoM) Coffs Harbour weather station - wind direction
- MHL tide gauge (located in inner harbour) - local water level

Table 3 presents a summary of the photographically recorded events that were available for this study. The table is presented in order of increasing hazard, as assessed by inspection of the event photographs.

Table 3: Coffs Harbour storm directional distribution

Date	Indicative Wave Direction[1]	Significant Wave Height (m)		Event Duration for H_s > 3m (hours)	Tide Conditions	Comment on hazard levels[2]
		Event Peak	Time of photos			
29 March 2011	SE	2.2	2.1	*3 m not exceeded*	Neap	Low hazard - minor splashing, unlikely that a pedestrian would get wet.
25 November 2010	E	2.1	1.5	*3 m not exceeded*	Spring	Low hazard – some splashing, possible for a pedestrian to get wet.
12 October 2010	E	3.4	2.8	8	Between spring and neap	Low hazard – splashing occurring, likely that a pedestrian would get wet. Uncomfortable but not dangerous.
6 March 2004	NE - E	4.0	3.8	24	Spring	Medium hazard – splashing reaching 3 – 4 m above breakwater crest. Possibly some wave run-up overtopping breakwater (see example below).
30 December 2007	ESE[3]	4	5	72	Between spring and neap	Medium hazard – splashing reaching 3 – 4 m above breakwater crest. Possibly some wave run-up and 'green water' overtopping breakwater.
22 May 2009	E	6.5	6.0	96	Between spring and neap	High hazard – 'green water' over breakwater crest. Structural damage occurred on breakwater crest (MHL, 2010).

Notes:

1. *Coffs wave rider buoy is non-directional, an indicative wave direction has been based on review of wave direction at Bryon and Sydney directional buoy's and local wind direction.*
2. *Hazard levels are defined from photographs taken during the event and are thus considered indicative only.*
3. *Wave direction for this event is considered to be uncertain.*

An example of the time series plots for these parameters for a period of 14 days (7 days before and after each photograph was taken) are provided in Figure 6. Examples of the associated photographs showing wave overtopping conditions are provided in Figure 7.

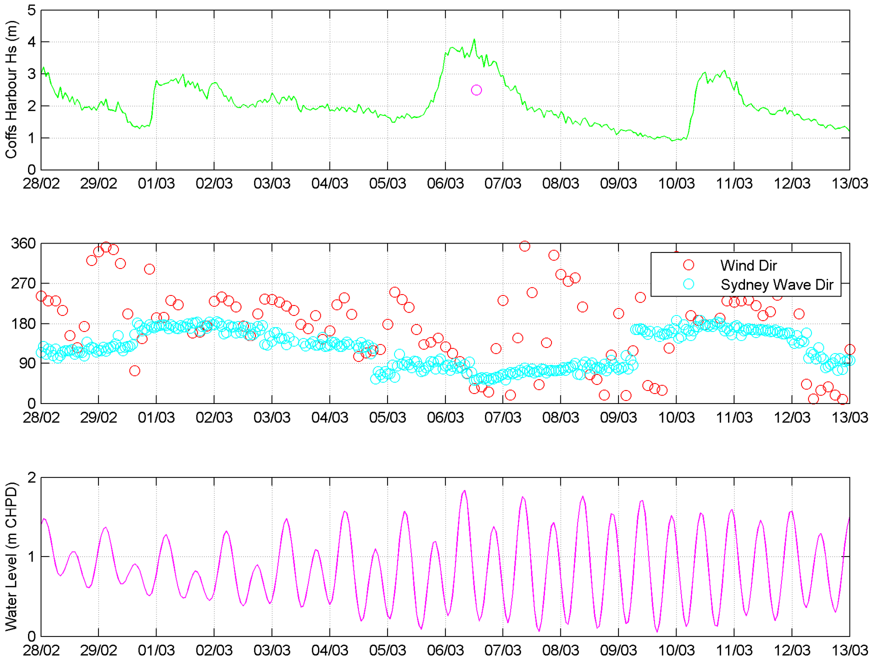

Figure 6: Metocean conditions around the 6 March 2004.

Figure 7: Observed wave overtopping conditions for the event on the 6 March 2004.

WAVE HEIGHT TRIGGERS

Table 4 provides the recommended wave height trigger levels for use in RMP.

Table 4: Recommended Significant Wave Height (H_s) Trigger Levels

Offshore Wave Direction	Wave Height (Hs) (m) for Wave periods (Tp) up to 14 secs	Wave Height (Hs) (m) for Wave periods (Tp) > 14 secs
NE to ESE	3.5	3.0
SE	4.5	4.0
SSE	5.5	5.0
S	6.0	5.5

As shown above, a wave period (T_p) trigger of 14 s has been defined. For wave periods greater than this trigger level wave height trigger levels should be reduced by 0.5 m as indicated in Table 4.

CONCLUSIONS

Based on investigations, available data, information available from forecasting websites and stakeholder consultation, the following recommendations are made:

- Adoption of an offshore significant wave height trigger level regime as recommended by Table 4.
- Implementation of an interim warning notification system
- Installation of a self-closing gate on the breakwater that prevents access onto the breakwater but allows access off the breakwater
- Installation of temporary barriers to access points from the marina to the breakwater
- Installation of associated permanent and temporary signage
- Installation of a directional waverider buoy at Coffs Harbour to assist in forecasting overtopping conditions at the breakwater
- Development of an automated warning notification system.

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