FORT DENISON

Sea Level Rise Vulnerability Study

Department of Environment & Climate Change NSW

Coastal Unit
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EXECUTIVE SUMMARY

ES1. Introduction

Fort Denison is recognized by the people of Sydney as an historic fortification that remains an enduring iconic feature in a changing harbour context. The history of the Fort and nature of its massive sandstone construction, combined with its isolation and comparative inaccessibility, adds to is landmark status within Sydney Harbour.

Fort Denison, previously known as *"Mat-te-wan-ye"*, *"Rock Island"* and *"Pinchgut",* serves as a stark and iconic reminder of Australia's rich colonial and convict heritage. In 1995, Fort Denison was added to the Sydney Harbour National Park and is currently managed as part of the Park by the NSW Department of Environment and Climate Change (DECC). Fort Denison was added to the State Heritage Register in 1999.

Perched in the middle of Sydney Harbour, Fort Denison is subjected to the continual physical processes of winds, tides, waves and associated currents. Although not exposed to high energy ocean swells, the site is directly impacted upon by a combination of wave climates comprising local wind driven seas and waves generated by the multitude of recreational and commercial vessels utilising this densely trafficked area of harbour.

To date, Fort Denison has generally withstood these constant processes reasonably well, with differential weathering of sandstone blockwork the main casualty of the passage of time. However, recent climate change induced sea level rise projections ranging between 20 and 100cm by the year 2100 will have a significant bearing on the management and utilisation of this iconic facility into the future.

ES2. Climate Change and Sea Level Rise

The latter half of the past century has been spent by the atmospheric scientific community investigating the magnitude of and broad range of impacts associated with, the postulated warming of the earth due to the accumulation of certain gases in the atmosphere ("Greenhouse Effect").

Although significant conjecture and international debate has centred on climate change and postulated impacts for over two decades, IPCC (2007) concludes *"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."* Further, IPCC (2007) warns *"Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas emissions were to be stabilised".*

Of all the impacts from climate change, the projected rise in mean sea level is the most significant concern for coastal zone managers. In addition to higher storm surge and oceanic inundation levels, a rise in mean sea level will also result in complimentary recession of unconsolidated (sandy) shorelines.

From detailed analysis of global tide gauge records, IPCC (2007) concluded that the rate of observed sea level rise increased from the 19th to 20th century and that the total

20th century rise was estimated to be 17 ± 5 cm. IPCC (2007) similarly concluded that global average eustatic sea level rise over the period from 1961 to 2003 is estimated at 1.8 ± 0.5 mm/yr.

The most accurate measured sea level rise data from satellite altimetry dating back to late 1992, indicates sea level rising during this period at approximately 3.1mm/year. **Although this is only a relatively short record, these rates equate to the upper limit trajectory for modelled sea level rise over the 21st century as projected by the Inter-governmental Panel on Climate Change (2001 and 2007).** At present, a synthesis of the best available scientific information suggests that sea level rise in Sydney Harbour due to climate change could range from around 4-38cm and 16-89cm by 2050 and 2100, respectively.

ES3. Vulnerability Assessment

The vulnerability assessment is primarily based on comparing current and future design still water and wave runup levels (incorporating sea level rise) with the existing level of infrastructure and assets on Fort Denison. For example, the crest level of the external walls of the Fort, decks and floor levels, all provide direct references to assess the likelihood or extent of overtopping and inundation expected due to particular sea level rise scenarios over various future planning horizons.

The vulnerability assessment of Fort Denison to climate change induced sea level rise has been based on three separate planning horizons, namely present day (2008), 2050 and 2100. Design still water levels of varying Average Recurrence Interval (0.02 to 100 years) have been considered along with “LOW”, “MEDIUM” and “HIGH” projected sea level rise scenarios. These design still water levels have been coupled with an “equivalent” or representative design wave climate to estimate wave runup ($R_{u2\%}$) levels around the periphery of the Fort for each planning horizon.

ES4. Key Vulnerabilities

The entry to the Western Terrace via the wharf is elevated at 1.41m AHD and is the lowest point (and therefore the most vulnerable area) for direct ingress of seawater around Fort Denison. This entry point is vulnerable to tidal inundation by seawater with an Average Recurrence Interval (ARI) of 50 years or more, in the absence of wave action.

The current design 100 year ARI still water level (1.435m AHD) is sufficient to cover the lowest surveyed point on the Western Terrace (1.34m AHD) forecourt by up to 95mm of seawater for possibly 30-60 minutes but would not enter doorway sill levels entering to the forecourt from the Barracks. Nonetheless, sub-flooring structures supporting the floorboards within the Barracks would be expected to be submerged by water levels with a more modest recurrence interval.

The projected 2050 design 100 year ARI still water level could be sufficient to cover the lowest surveyed point on the Western Terrace forecourt by between 13 and 48cm with seawater, depending on the sea level rise scenario considered. Similarly, several floors within the “Barracks” could be expected to be submerged to varying levels within this range similarly depending on the still water level ARI and sea level rise scenario.

By 2100, under a “HIGH” sea level rise scenario, the entry point is predicted to be vulnerable to tidal inundation by ocean waters where the hourly water level would be reached as often as 50 times per year. Under a “HIGH” sea level rise scenario, the 100 year ARI still water level would be some 80cm above the lowest floor level in the Barracks by the turn of the century.

The lowest crested seawall structures around Fort Denison are the Western Seawall (2.67 – 2.79m AHD) and the curvilinear wall around the Slipyard/BBQ area (2.84m AHD). Both walls are currently exceeded by the 100 year ARI design wave runup level by over 2m. No other external wall structures are threatened by design wave runup and overtopping to 2100 under any of the sea level rise scenarios.

ES5. Conclusions

It is likely that the current configuration of the Fort could continue to be effectively managed with minor modifications (raising floor levels where necessary to combat a modest rise in sea level of possibly 10-20cm).

However, inundation from sea water due to larger sea level rises will substantially compromise the useability and general accessibility of the site as well as the maintenance of the built heritage assets, flooring systems, etc. Under these circumstances significant alterations may be necessary to continue use of the site whilst accommodating a mean sea level rise of up to 1m. These alterations would include: blocking up the existing entry point with a continuous Western Seawall, sealing the foundations and external blockwork to prevent seepage and direct ingress of seawater and consideration of increasing the crest of existing seawalls or introducing wave deflector capping to limit potential wave runup and overtopping from entering the site.

It is important to appreciate that sea level rise is projected to increase on an increasing trajectory, well beyond the conventional planning horizon of 2100. Under these circumstances, and in the absence of substantial changes to the integrity of the current built form, Fort Denison will become a successively submerged artefact over an indeterminate timeframe, well into the future. Similarly, it is important to recognise that although every effort has been made to provide the most up to date advice within this report on climate change induced sea level rise, projections of sea level rise over longer term planning horizons are uncertain and continually evolving and will be driven by global socio-political climate change policy, continued advancements with climate change modelling and success in limiting greenhouse gas emissions.

In the interim, future planning at Fort Denison, which is particularly vulnerable to climate change induced sea level rise can be guided by the implications of the advice contained within this report and updated at not more than 10 yearly intervals in order to stay abreast of advancements regarding both the monitoring and projections of this significant phenomenon.

TABLE OF CONTENTS Page No.

LIST OF FIGURES Page No.

LIST OF TABLES Page No.

LIST OF TABLES (Continued) **Page No.**

APPENDICES

Appendix A: Bureau of Meteorology Wind Data - Sydney Airport AMO

Appendix B: Fort Denison Tide Level Analysis (Manly Hydraulics Laboratory)

Appendix C: Sydney Harbour Design Still Water Analysis (Gumbel Probability Distribution)

Appendix D: Design Wave Field for Fort Denison

Appendix E: Design Wave Runup Assessment

Appendix F: Photos around Fort Denison taken on 26 November 2007 coinciding with measured 1.95m ISLW peak tide event (Photos courtesy Cath Snelgrove and Rebecca Wise, DECC)

Appendix G: Photos around Fort Denison Delineating Survey Levels of Relevant Features (Photos courtesy Phil Watson, DECC)

1 PREFACE

The Coastal Unit, Department of Environment and Climate Change (DECC) have prepared this technical report for the Heritage Section within DECC's Parks and Wildlife Group (Sydney Region) to define the nature and extent of physical coastal processes impacting upon Fort Denison. This report investigates the vulnerability of the Fort to projected sea level rise from climate change to 2100 which will assist with long-term strategic planning and management of this iconic, heritage listed asset.

This report is one of three in a series covering the additional heritage listed sites of Goat Island and Nielsen Park, Vaucluse.

It is recognised that climate change research, knowledge and understanding are part of a rapidly and continually evolving science. Every effort has been made to incorporate state of the art understanding of climate change induced sea level rise at the time of writing. It is therefore recommended that this report is reviewed and updated at regular intervals into the future (not greater than 10 years) in order to accommodate relevant advancements in climate change knowledge and planning responses.

Figure 1.1: Fort Denison, Sydney Harbour. Photo courtesy Tourism NSW.

2 INTRODUCTION

Fort Denison is situated on a small rock promontory in the middle of Sydney Harbour, situated some 1.3km due east of the Harbour Bridge (refer Figure 2.1). Fort Denison is a relatively diminutive structure, measuring approximately 88m in length by 30m in width, covering an area of approximately 2600m^2 (refer Figure 2.2).

Once a rock promontory extending to 25m above mean sea level, the island was flattened in the early 1800s. The existing fortification was constructed during the 1850s using 8000 tonnes of sandstone quarried from nearby Kurraba Point, Neutral Bay to sit atop the natural underlying rock.

At its highest point, the Martello Tower on the north-eastern end of the island sits at approximately 15.4m above mean sea level (refer Figure 2.2). Surrounded by water, Fort Denison, previously known as *"Mat-te-wan-ye"*, *"Rock Island"* and *"Pinchgut",* serves as a stark and iconic reminder of Australia's rich colonial and convict heritage. In 1995, Fort Denison was added to the Sydney Harbour National Park and is currently managed as part of the Park by the NSW Department of Environment and Climate Change (DECC).

Figure 2.1: Locality Plan. Image courtesy Google Earth.

Fort Denison offers guided tours by National Parks and Wildlife Service Guides and a café/function facility is operated on the island under a commercial lease. Fort Denison also houses one of the worlds longest continuous tide gauge recording facilities, which was first established on the island in the 1860s.

Perched in the middle of Sydney Harbour, Fort Denison is subjected to the continual physical processes of winds, tides, waves and associated currents. Although not exposed to high energy ocean swells, the site is directly impacted upon by a combination of wave climates comprising local wind driven seas and waves generated by the multitude of recreational and commercial vessels utilising this densely trafficked area of harbour.

To date, Fort Denison has generally withstood these constant processes reasonably well, with differential weathering of sandstone blockwork the main casualty of the passage of time. However, recent climate change induced sea level rise projections ranging between 20 and 100cm by the year 2100 will have a significant bearing on the management and utilisation of this iconic facility into the future and are examined in detail within the study.

Figure 2.2: Aerial view Fort Denison (2008). Image courtesy Google Earth

3 HISTORICAL CONTEXT

The island on which Fort Denison (the Fort) now stands was once a 25m high rocky outcrop known to the Aboriginal people as Mat-te-wan-ye.

In 1839 two American sloops entered the harbour undetected and caused alarm over the inadequacy of the Sydney defences. This prompted the first phase of building on the island including quarrying the rocky outcrop to create a level gun battery. This was completed in 1842.

Further concern about the state of the harbour defences arose with the outbreak of the Crimean War between Russia and England in the mid 1850s. As a result, plans were drawn up to create a fort with barracks and the characteristic Martello tower. This stage of building used both stone from the island itself as well as stone quarried from Kurraba Point, Neutral Bay.

In 1857 the Fort was named Fort Denison after Governor Denison and was ready for battle with ten, 8 and 12 inch, 32 pounder cannons. The guns were never needed outside practice and were never fired in anger. The Fort was abandoned as a military installation in the 1870s. The development of iron clad ships and improved weapons made the Fort obsolete and development of the harbour's defences concentrated on the outer harbour from this time onwards.

The Fort has been a reference point for tide measurement since 1870. There are currently two tide gauges on the Fort, the modern electronic gauge and the early gauge installed in 1908 which is still in operating order. The 1 o'clock gun was transferred from Dawes Point and has been fired at Fort Denison since 1906.

Fort Denison is of solid stone construction combining both the use of the remnant natural bedrock and quarried stone. The stone walls of the fort at the base of the tower are up to 4m thick tapering up to just over 2m at the top of the tower.

Fort Denison still retains the integrity of its completed 1862 form. In an international context, the combination of a Martello tower and associated barracks is unusual and rare. The Fort, built entirely of local sandstone, demonstrates the evolution from an island to convict shaped rock battery, to a completed Fort.

The Martello Tower on Fort Denison is unique as a European styled coastal fort constructed in Australia. It is of international significance as one of only two Martello towers in the southern hemisphere that survive intact. It forms part of a worldwide group of similarly styled and dated European coastal fort towers built during this period. The tower is also of international significance for the integrity of its original casemated ordnance and sidearms.

Fort Denison is recognized by the people of Sydney as an historic fortification that remains an enduring feature in a changing harbour context. The very nature of its massive sandstone construction, combined with its isolation and comparative inaccessibility, adds to is landmark status within Sydney Harbour.

Fort Denison currently receives about 7000 visitors a year. This number is expected to rise as new tour programs are developed and promoted.

A three year stonework conservation program is currently being undertaken on Fort Denison in conjunction with the Department of Commerce's Centenary Stonework Program. This program aims to address outstanding maintenance and repair issues on the Fort and to undertake research into key threatening processes, including the process of sea level rise.

4 DATA SOURCES

4.1 Introduction

When undertaking a vulnerability assessment of various assets in the coastal zone to climate change impacts, the success of the exercise will ultimately hinge on the accuracy of the climate change projections (refer Section 6) and the quality of critical data sets necessary to analyse the projected impacts including: hydrographic survey data, land survey data, orthophoto imagery and historical water level data.

4.2 Survey Data

Despite the historical significance and age of Fort Denison, there was extremely limited survey detail relating to levels of interest (including the crest and toe of external walls, floor levels, deck structures, etc) that could be directly correlated to projected future design ocean water levels under various climate change scenarios. Similarly, although considerable hydrographic survey data exists within Sydney Harbour to delineate and monitor shipping channels, there was limited data to describe the nearshore bathymetry from deepwater to the toe of the external walls of the Fort.

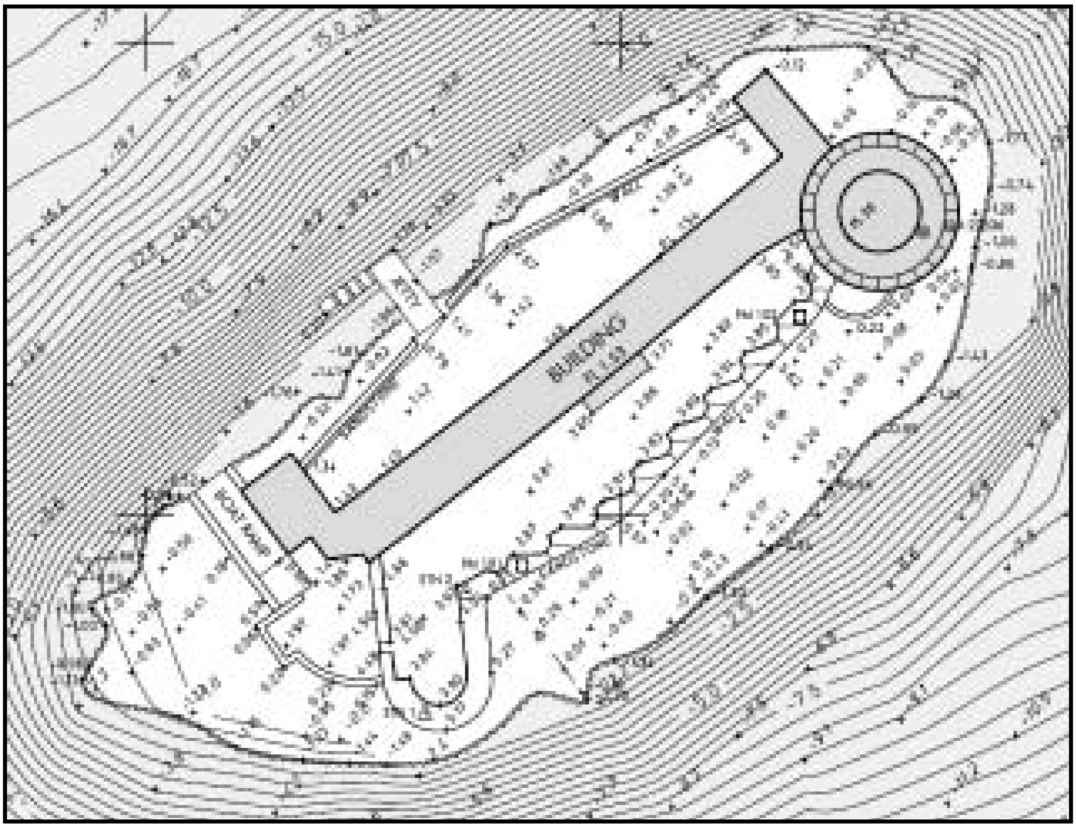


Figure 4.1: Extract from detailed survey plan of Fort Denison. Levels and contours indicated are in metres based on Australian Height Datum.

On 26 February 2008, DECCs Coastal Unit re-established pre-existing survey marks on the Martello Tower and south-eastern outer wall of the Fort using GPS survey techniques. These marks were used as the base station for use in accurately fixing positions measured during the detailed hydrographic survey of the waters surrounding Fort Denison on 27-28 February 2008. The survey involved DECC's vessel "Sea Scan" taking sonar readings of the sea bed around the Fort through a series of parallel ESE-WNW runlines at 10 metre spacings and an orthogonal set of runlines at 100m spacings.

On 10 April 2008, conventional land based GPS survey techniques were employed to recover levels of all relevant land based features on the Fort such as decks, floors, crests and toe of external wall structures, etc (refer Table 4.1).

Both sets of data have been merged into a seamless digital terrain model to produce a detailed contour plan of Fort Denison and the adjacent sea bed of Sydney Harbour. This allows accurate assessment of the implications of design ocean water levels under various sea level rise scenarios over differing planning horizons (refer Figure 4.1).

Table 4.1: Survey Levels of Relevant Features at Fort Denison

Feature	RL (metres AHD)
Floor of Tide Room	1.78
Floor of Kitchen Storage Room	1.68
Floor of Kitchen	1.58
Floor of Restaurant	1.54
Floor of Museum	1.63
Floor of Amenities (Ladies)	1.58
Floor of Amenities (Gents)	1.61
Floor of Entry to Eastern Terrace	1.53
Bitumen forecourt of Western Terrace	1.34 – 1.48
Entry to Western Terrace	1.41
Floor at entry to Martello Tower	3.54
Floor in Martello Tower (Gunpowder Room)	1.23
Floor in Martello Tower (Cannon Room)	6.89
Crest of Western Seawall	2.67 – 2.79
Natural surface of slipyard/BBQ area	1.73 – 1.97
Crest of linear seawall around BBQ facility	3.49 -3.60
Crest of curvilinear seawall around slipyard/BBQ area	2.84
Crest of Eastern Seawall	5.57 – 5.62
Grassed Eastern Terrace	3.65 – 3.94
Top of Martello Tower	15.38
Crest of curvilinear seawall around the Bastion	5.17 – 5.27

Notes:
1. Levels are in metres to Australian Height datum (AHD);
2. Refer Figure 2.2 for location of relevant features; and
3. The levels of various features are illustrated pictorially in Appendix F.

4.3 Orthophoto Imagery

There is a wide range of aerial photography available for the Sydney basin however, the majority is generally at a relatively high scale (larger than 1:25,000), insufficient for use in GIS style mapping processes concerning Fort Denison because it is a relatively small feature.

The Coastal Unit engaged AAMHatch to capture low level, high resolution vertical aerial photography of the foreshores and relevant islands within the Sydney Harbour National Park at a scale of approximately 1: 6000. The photography was flown mid morning on 4 March 2008 on the falling tide. The resulting high resolution, low scale imagery has been ortho-rectified to ground survey control points to provide a baseplan fitted to the available survey data and co-ordinate grid system.

The ortho-rectified imagery of 4 March 2008, provides up-to-date baseline mapping at high resolution and low scale enabling direct scaled measurements from the photography and accurate overlay of contour data and other planimetric information for analytical and presentation purposes.

4.4 Water Level Data

Water level recording commenced at Fort Denison with the first entry in the Tide Register dated 11 May 1866. However, data prior to June 1914 contain various errors which render the records unreliable (Hamon, 1987). The continuous record of reliable ocean water levels from the Fort Denison tide gauge facility since 1914 provides an exceptional data record for Sydney Harbour. The recorded water levels include components of astronomical tide as well as anomalies or variations from the predicted tide resulting from meteorological, oceanographic and harbour processes. Similarly, the data inherently incorporates climate change induced sea level over this timeframe.

Continuous hourly water level recordings are available from the Fort Denison tide gauge for the period from 31 May 1914 to present. Manly Hydraulics Laboratory have analysed the 794,400 available hourly data points to provide a summary of the normalised distribution of measured water levels for each cm graduation in height (refer Appendix B). DECC has analysed this data by assigning a probability distribution function to determine design still water levels for Sydney Harbour for various ARIs (refer Appendix C).

5 PHYSICAL PROCESSES

5.1 Introduction

Surrounded by the tidal waters of Port Jackson, Fort Denison is subjected to a range of physical processes including wind, waves, tidal fluctuations and associated currents. Each of these processes contribute to the elevation of the water surface around the island and the extent to which inundation, from wave breaking, runup and overtopping of the foreshore structures, is experienced on rare occasions.

This section summarises the extent of the contributions of each of these components on the water levels currently experienced at Fort Denison. Section 6 will consider the implications of climate change on these parameters and the associated impacts on existing infrastructure at Fort Denison to 2100.

5.2 Wind

Wind is a particularly important physical process in a harbour environment due to its capacity to transfer energy to the water surface to create currents and generate wave climates. Wave height and period are closely related to wind speed. As such, it is possible to reconstruct wave climates at a site from historical, measured wind records using a procedure known as wave hindcasting. There are several simplified methods available for estimating wave fields from wind records, most commonly those measured from local or nearby airports.

Wind data from Sydney Airport, which is located approximately 10km from Fort Denison is available spanning 69 years (1939 to 2008) from the Bureau of Meteorology. Wind roses for 0900 hrs and 1500 hrs spanning this timeframe (refer Appendix A) indicate that in the morning, wind is predominantly directed from the north-west (29%), west (19%) and south (16%). However, in the afternoons, the predominant wind directions have a comparatively more easterly bias, directed from the south (22%), north-east (20%) and south-east (16%).

The 10 minute average wind speed measured at Sydney Airport not only indicates a distinct difference in the wind speeds and direction between morning and afternoon, but, a considerable seasonal bias with the minimum monthly average inclined toward late autumn and the maximum monthly average generally expected in late spring/early summer (refer Appendix A).

Further analysis of the 10 minute average wind speed data from Sydney Airport indicates that wind speeds between 51 and 60 km/h have been recorded from all primary directions with the most significant wind speeds predominantly directed from the south and south-east, reaching between 91 and 110 km/h. Table 5.1 provides a summary of the percentage frequency of mean 10 minute average wind speeds based on the Sydney Airport wind data.

Table 5.1: Percentage Frequency of Mean 10 Minute Average Wind Speed Sydney Airport AMO (1939 to 2008)

Speed (km/h)	DIRECTIONS								
	N	NE	E	SE	S	SW	W	NW	All
1-10	3	2	2	2	2	2	5	7	**26**
11-20	3	4	3	4	4	2	4	4	**29**
21-30	2	4	1	3	6	2	2	1	**20**
31-40	X	1	X	1	3	1	1	X	**7**
41-50	X	X	X	X	1	X	X	X	**3**
51-60	X	X	X	X	X	X	X	X	**1**
61-70	X	X	X	X	X	X	X	X	**X**
71-80			X	X	X	X	X	X	**X**
81-90				X	X	X	X		**X**
91-100				X	X				**X**
101-110					X				**X**
111-120									
121-130									
131-140									
>140									
All	**9**	**11**	**7**	**10**	**16**	**7**	**13**	**13**	**86**

Source: Bureau of Meteorology (2008)

Notes: 1. Values are percentage frequencies.
2. "X" indicates the range has occurred but with a frequency of less than 0.5%.
3. Calm conditions were measured on 14% of occasions.
4. A total of 194,308 observations were analysed.

5.3 Waves

Waves are a fundamental design constraint in coastal waters providing a source of energy that is dissipated against structures or foreshores and contributing to elevated water levels that lead to overtopping and inundation (refer Section 5.4.2). Waves are more prominent features on the open coast of NSW and are generally defined as either ocean swell (generated from winds in the deep ocean with long periods) or seas (generated from local wind sources).

Fort Denison is situated some 6km from the ocean entrance at South Head and is not exposed to long period, high energy swell wave activity. The majority of swell wave energy directed into the harbour is dissipated on the shorelines around Middle Head. Swells modified by refraction and diffraction processes have been observed to penetrate into the harbour as far as Nielsen Park and Rose Bay. Modelling of wave processes by Cardno Lawson Treloar (CLT) indicate that swell wave activity within the harbour is confined to the east of that portion of Port Jackson between Bradleys Head and Point Piper, some 2km east (or seawards) of Fort Denison (*pers. comms* Doug Treloar, CLT).

Although Fort Denison is not subjected to ocean swell waves, the site is exposed to local wind driven seas. These seas are comprised of comparatively low energy and short period waves superimposed on wave fields generated from the multitude of recreational and commercial vessels using the heavily trafficked working harbour. Very small, extremely long period waves (including tsunami) associated with strong currents have also been known to impact upon Sydney Harbour in the past.

Wave energy is a function of both the wave height and wave period (the time between successive wave crests). As such, the extent of wave energy dissipated around natural harbour foreshores or against fixed structures and revetments will vary depending on the derivation of the wave source. Within most harbour or estuary confines, wind generated waves are limited to heights of 0.2 to 0.5m and periods ranging from 2 to 4 seconds, depending on available wind fetch lengths and the strength of prevailing winds (Edwards & Lord, 1998). Boat generated waves within speed restricted navigable harbours and estuaries of NSW are generally limited, though the wave periods generated by some vessels have been measured in the range more commonly associated with high energy deep ocean swell (8 to 10 seconds). Where boat generated waves have a higher wave energy than those from the existing wind wave environment, a disproportionate increase in the erosion of banks and foreshores could be expected.

The changing wind patterns and wide variety of boat wave signatures create wave fields approaching Fort Denison that are highly variable, random and exceedingly complex. For design purposes it would be preferable to have long-term wave data records from within the harbour that automatically record the totality of the wave field. This is rarely the case and indeed no such record exists for the waters in the vicinity of Fort Denison. Under these circumstances, it is valuable to separate out the relevant contributions from locally generated seas and that of boat generated waves in order to look at their respective impacts.

With knowledge of individual wind and boat wave climates, an “equivalent” or representative wave field for design purposes can be developed that considers the likelihood of both wind driven seas and boat generated wave fields occurring simultaneously.

Appendix D provides a detailed assessment of design wave climates relevant to Fort Denison. The largest wind generated waves impacting upon Fort Denison are directed through the east to south quadrant and estimated to range in height up to 0.71m with a corresponding period of 2.3s (refer Table D1). Similarly, the largest boat wave inside Sydney Harbour is estimated to have a height of 0.87m with periods ranging up to 10s (refer Table D2).

5.4 Ocean Water Levels

At any given time, ocean water levels are continually influenced by meteorological and oceanographic processes superimposed on the prevailing astronomical tide.

It is therefore of importance to understand the contributions of each of these components (particularly during extreme oceanic storm events) in order to assess probable inundation levels for design, planning and management purposes. In addition to these identified components contributing to elevated ocean water levels, currently measured and projected climate change induced sea level rise will have a significant bearing on design ocean water levels over future planning horizons and will be discussed separately in Section 6.

5.4.1 Astronomical Tide

The astronomical tide component of a given ocean water level, is based upon the combined influences of the Sun and the Moon and their position relative to the Earth at given point in time. The tide is in effect a very long period wave set in motion by the centrifugal force of the rotating earth on the ocean and is governed by the gravitation forces applied by the Moon, Sun and other planets. The Moon, with a gravitational influence almost twice that of the Sun, is the primary factor controlling the temporal rhythm and height of the tide.

The NSW coastal zone experiences semi-diurnal tides, which consist of two high and two low tides daily. The larger or “spring” tidal range (generally 1.8 to 2.2m), occurs when the moon is full (or new) and the gravitational pull of the moon and sun are combined. Solstice or “king” tide conditions occur more frequently around Christmas and during the mid-winter months when the sun, moon and earth are aligned, exhibiting the most significant gravitational influence on the ocean water surface.

With knowledge of the amplitude and harmonics of all lunar and solar constituents over the full lunar nodal cycle (18.6 years), astronomical tide charts are able to be forecast with considerable accuracy well into the future.

5.4.2 Oceanographic and Harbour Processes

In an exposed open ocean situation, the most significant components of elevated ocean water levels are the combined processes of wave setup and wave runup on beaches. These processes alone can super elevate the water level at the shoreline by as much as 7.0m above the still water level of the ocean under extreme oceanic storm wave activity.

The wind and boat wave climate on Sydney Harbour in the vicinity of Fort Denison is comparatively less than that experienced on the open coast from swell. However, runup from wave energy dissipation against the external stone walls of the Fort is still significant. Near vertical, blockwork structures, may be liable to intense local wave impact pressures and may overtop suddenly or severely, reflecting much of the incident wave energy (EurOtop, 2007).

The height of runup from waves dissipating energy against an impermeable vertical stone wall depends on several factors including wave height and period, profile of the nearshore area, depth of water and wave regularity. The water depth in particular at the toe of the structure relative to the size of the wave can dramatically alter the capacity of the wave to break at the structure.

The actual runup from waves is a relatively dynamic and highly variable phenomena which is usually expressed as a height measured vertically above the still water level (R_u), exceeded by a small percentage of waves. A detailed assessment of design wave runup levels at Fort Denison is presented in Appendix E.

In addition to boat and wind waves elevating the water surface, confining a water body in the form of a harbour can also induce a range of long period oscillations (typically 30s to 10min) that are characterised by small vertical amplitudes, but, with large horizontal movements. These oscillations are complex and governed by the physical dimensions of the harbour and the water depth and can be quite destructive when the period of the oscillation coincides with (and is amplified by) the natural resonant period of the harbour. This phenomenon is often referred to as harbour resonance or seiching (USACE, 2002).

5.4.3 Meteorological Processes

The ocean water level can vary significantly from that of the predicted tide due to meteorological processes including storms, extreme winds and changes in the mean sea level air pressure. As a liquid, the sea surface can be readily deformed by wind and changes in atmospheric pressure.

Tide projections are based upon normal barometric pressure at mean sea level (1013 hPa). The reduced barometric pressures associated with “low” pressure weather systems which generate strong storm winds, also cause a local rise in the ocean water surface (known as the *“inverse barometer effect”).* Provided low pressures persist for a sufficient length of time, the increase in water level amounts to approximately one centimetre for each hPa drop in pressure below 1013 hPa. This phenomenon and its affect on elevating the ocean water surface during a storm event is termed *“barometric setup”* and has been measured in the order of 0.2 to 0.4m in NSW coastal waters (NSW Govt, 1990).

Extreme wind speeds not only generate local seas but, also tend to pile water up against a shoreline in the direction of the wind. The component of increasing water level attributable to wind action is termed *“wind setup”* and is of the order of 0.1 to 0.2m (NSW Govt, 1990).

The vast majority of adverse weather systems which impact upon the Sydney basin are “low” pressure systems bringing significant precipitation and generating intense wind speeds. Under these circumstances, the super-elevation of the ocean water surface due to the combined effects of *“barometric”* and *“wind setup”* is termed *“storm surge”.*

Major meteorological phenomena such as the El Niño-Southern Oscillation (ENSO) affect water levels along the NSW coastline (NSW Govt, 1990). Much of the variability of Australia’s climate is connected with the atmospheric phenomena called the Southern Oscillation, a major see-saw of air pressure and rainfall patterns between the Australia/Indonesian region and the Eastern Pacific. The Southern Oscillation is measured by a simple index, the Southern Oscillation Index (SOI), which can be related to specific changes in the temperature of the underlying ocean, commonly referred to as El Niño and La Niña events. The SOI is calculated from the monthly fluctuations in the mean air pressure difference between Tahiti and Darwin (BoM, 2008).

Sustained negative values of the SOI indicate El Niño episodes which are usually accompanied by sustained warming of the central and eastern tropical Pacific Ocean, cooling of the oceans around Australia and a reduction in rainfall over eastern and northern Australia (BoM, 2008). Conversely, positive values of the SOI are associated with stronger Pacific trade winds and warmer sea surface temperatures to the north of Australia, are popularly known as a La Niña episode.

Together, these give an increased probability that eastern and northern Australia will be wetter than usual (BoM, 2008).

The sea level anomalies around Australia generally follow the Southern Oscillation Index (SOI); higher average sea levels coincide with high values of the SOI (La Niña) and lower average sea level coincides with low values of the SOI (El Niño). It follows that the El Niño - Southern Oscillation cycle is a major influence on sea levels around Australia (NTC, 2007). The associated water level change along the NSW coastline attributable to ENSO is estimated in the order of ±0.1m (NSW Govt, 1990).

5.4.4 Tectonic Processes

The two tectonic processes which could potentially affect water levels along the NSW coast are earthquakes generated by subsidence of the crustal plate on which the coastline of NSW rides and undersea landslides (NSW Govt, 1990).

Tsunami which are caused by undersea earthquakes, are incorrectly referred to as “tidal waves”. Although Australia is remote from the more seismic areas of the world, water level anomalies along the NSW coast due to tsunamis have indeed occurred, but are rare (NSW Govt, 1990).

Studies of Fort Denison tide gauge records from 1867 onwards have identified a number of water level anomalies due to tsunami, the three largest of which occurred in 1868, 1877 and 1960 (PWD, 1985). Water level changes of 1.07m accompanied the 1868 and 1877 events. In 1960 a tsunami resulting from a severe earthquake in Chile caused the water level at Fort Denison to oscillate through a range of 0.84m over a 45 minute period. These rapid water level changes induced strong currents in Sydney Harbour and nearby ports and bays, causing considerable damage to boats and shoreline structures. The damage caused by this tsunami was exacerbated by the semi-enclosed nature of Sydney Harbour. The tsunami probably occurred without notice along the open coastline (NSW Govt, 1990).

Tsunami occur on a random basis and are independent of all other effects causing elevated water levels. The simultaneous occurrence of elevated water levels due to a major storm event and a tsunami is most unlikely (NSW Govt, 1990).

5.4.5 Tidal Anomalies

A tidal anomaly is referred to as the difference between the measured ocean water level and the predicted tide. The tidal anomaly can result from the complex interaction of local seas and several of the aforementioned meteorological, oceanographic and harbour processes occurring simultaneously.

The tide gauge facility on Fort Denison has been recording ocean water levels since 1866 and is the longest continuous record of ocean water levels in NSW. Water levels have been measured continuously at Fort Denison for over 100 years though the data is considered reliable for the period since June 1914 (Hamon, 1987). Over this timeframe, the largest tidal anomaly measured is 59cm and was recorded on 26 May 1974 during the most significant oceanic storm event on the historical record (MHL, 1997).

5.4.6 Design Water Levels

The continuous record of reliable ocean water levels from the Fort Denison tide gauge facility since 1914, provides an exceptional data record for Sydney Harbour. The data reflect the astronomical tide levels as well as anomalies or variations from the predicted tide resulting from the range of sources discussed in Sections 5.4.2 to 5.4.4 and other unidentified sources. Similarly, the data inherently incorporates climate change induced sea level over this timeframe.

Continuous hourly water level recordings are available from the Fort Denison tide gauge data for the period from 1 June 1914 to present. Manly Hydraulics Laboratory have analysed the 794,400 available hourly data points to provide a summary of the normalised distribution of measured water levels for each cm graduation in height (refer Appendix B). Table 5.2 summarises the record high and low water level recordings at Fort Denison over this timeframe.

Table 5.2: Record Water Level Events at Fort Denison

Maximum Recorded Water Levels		
ISLW (metres)	**AHD (metres)**	**Date (time)**
2.40	1.475	25 May 1974 (2300 hrs)
2.35	1.425	27 April 1990 (2200 hrs)
2.32	1.395	10 June 1956 (2100 hrs)
2.27	1.345	30 June 1984 (2200 hrs)
2.27	1.345	19 August 2001 (2000 hrs)
Minimum Recorded Water Levels		
ISLW (metres)	**AHD (metres)**	**Date (time)**
-0.19	-1.115	20 August 1982 (0300 hrs)
-0.18	-1.105	24 December 1999 (1600 hrs)
-0.17	-1.095	18 July 1924 (0400 hrs)
-0.17	-1.095	3 September 1925 (0200 hrs)
-0.17	-1.095	24 August 1926 (0300 hrs)
-0.17	-1.095	29 September 1926 (0200 hrs)
-0.17	-1.095	4 September 1927 (0300 hrs)
-0.17	-1.095	14 September 1927 (1500 hrs)
-0.17	-1.095	16 January 1938 (1500 hrs)
-0.17	-1.095	23 October 1945 (1600 hrs)

Notes: Based on hourly measurements (31 May 1914 to 31 December 2006).

There are a broad range of probability distribution functions available for application in estimating extreme values. For many coastal design parameters, for example ocean wave heights, there may only be a maximum of 20 to 30 years of quality recorded data. The application of extreme value theory is therefore required to extrapolate design values with a recurrence interval significantly longer than that of the data record. Appendix C summarises an extreme value analysis of the available water level data using the Gumbel probability distribution function, to estimate design still water levels for Sydney Harbour. Relevant design levels are summarised in Table 5.3.

Table 5.3: Sydney Harbour Design Still Water Levels

ARI (years)	Maximum Level	
	m ISLW	m AHD
0.02	1.89	0.965
0.05	1.97	1.045
0.10	2.02	1.095
1	2.16	1.235
2	2.20	1.275
5	2.24	1.315
10	2.27	1.345
20	2.30	1.375
50	2.34	1.415
100	2.36	1.435
200	2.38	1.455

Notes:
1. Values derived from Figure C2 (Appendix C).
2. ISLW refers to Indian Springs Low Water Datum.
3. AHD refers to Australian Height Datum.
4. For conversion from ISLW to AHD, subtract 0.925m.

6 CLIMATE CHANGE AND SEA LEVEL RISE

6.1 Introduction

The latter half of the past century has been spent by the atmospheric scientific community investigating the magnitude of and broad range of impacts associated with, the postulated warming of the earth due to the accumulation of certain gases in the atmosphere ("Greenhouse Effect").

The most authoritative source on the impacts of climate change is the Inter-governmental Panel on Climate Change (IPCC). The IPCC was established under the auspices of the World Meteorological Organisation and the United Nations Environment Programme to consolidate international scientific advancements in climate change research. On 2 February 2007, Working Group I of the IPCC adopted the Summary for Policymakers of the first volume of "Climate Change 2007" (IPCC, 2007), also known as the Fourth Assessment Report (AR4).

Although significant conjecture and international debate has centred on climate change and postulated impacts for over two decades, IPCC (2007) concludes *"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."* Further, IPCC (2007) warns *"Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas emissions were to be stabilised".*

Of all the impacts from climate change, the projected rise in mean sea level is the most significant concern for coastal zone managers. In addition to higher storm surge and oceanic inundation levels, a rise in mean sea level will also result in complimentary recession of unconsolidated (sandy) shorelines.

Depending on the rate and scale of sea level rise, the environmental, social and engineering consequences within low lying intertidal areas, in particular, will be profound. In addition to open coast recession and higher inundation levels, salt water penetration and more landward advance of tidal limits within estuaries will, amongst other things, have far reaching implications for aquatic freshwater and saltwater ecosystems. Similarly, existing coastal gravity drainage and stormwater infrastructure systems may become severely compromised over time as mean sea level rises. Waterfront properties with ambulatory boundaries (referenced to the mean high water mark) will also be impacted as the boundary feature moves successively landward over time with the land becoming more vulnerable to inundation over time. Seawalls and other coastal defence systems will also have to be incrementally upgraded over time to address the increasing threat from larger storm surges and inundation at higher projected water levels.

IPCC (2001) determined global sea level rise to be a function of time and comprising the following seven primary components:

- Thermal expansion;
- Loss of mass of glaciers and ice caps;

- Loss of mass of the Greenland ice sheet due to projected and recent climate change;
- Loss of mass of the Antarctic ice sheet due to projected and recent climate change;
- Loss of mass of the Greenland and Antarctic ice sheets due to ongoing adjustment to past climate change;
- Runoff from thawing of permafrost; and
- Deposition of sediments on the ocean floor.

6.2 Measurements of Sea Level Rise

"Mean sea level" at the coast is defined as the height of the sea with respect to a local land benchmark, averaged over a period of time, such as a month or a year, long enough that fluctuations caused by waves and tides are largely removed. Changes in mean sea level measured by coastal tide gauges are called "relative sea level changes", because they can come about either by movement of the land on which the tide gauge is situated or by changes in the height of the adjacent sea surface (both considered with respect to the centre of the Earth as a fixed reference). These two terms can have similar rates (several mm/yr) on time-scales greater than decades (NTC, 2007).

To detect eustatic sea level changes arising from changes in the ocean, the movement of the land needs to be subtracted from the records of tide gauges and geological indicators of past sea level. Widespread land movements are caused by isostatic adjustment resulting from the slow viscous response of the Earth's mantle to the melting of large ice sheets and the addition of their mass to the ocean since the end of the most recent glacial period ("Ice Age"). Tectonic land movements, atoll decay, rapid displacements (earthquakes) and slow movements (associated with mantle convection and sediment transport) can also have an important effect on local relative sea level (NTC, 2007).

Measurements of sea level rise have been identified from several data sources including long-term tide gauge records and more recent technologies including satellite altimetry.

6.2.1 Tide Gauge Records

Sea level rise has been evident from a range of very long-term water level gauges stationed around the world, particularly those in northern Europe (refer Figure 6.1). The two longest continuous tide gauge records in Australia, Fremantle (from 1897) and Fort Denison (from 1914) exhibit similar qualitative trends in increasing sea level over time. Church and White (2006) advised that the change of relative mean sea level around the Australian coastline from analysis of tide gauge records for the period 1920 to 2000 is about 1.2mm/year.

From detailed analysis of global tide gauge records, IPCC (2007) concluded that the rate of observed sea level rise increased from the 19th to 20th century and that the total 20th century rise was estimated to be 17 ± 5 cm. IPCC (2007) similarly concluded that global average eustatic sea level rise over the period from 1961 to 2003 is estimated at 1.8 ± 0.5 mm/yr.

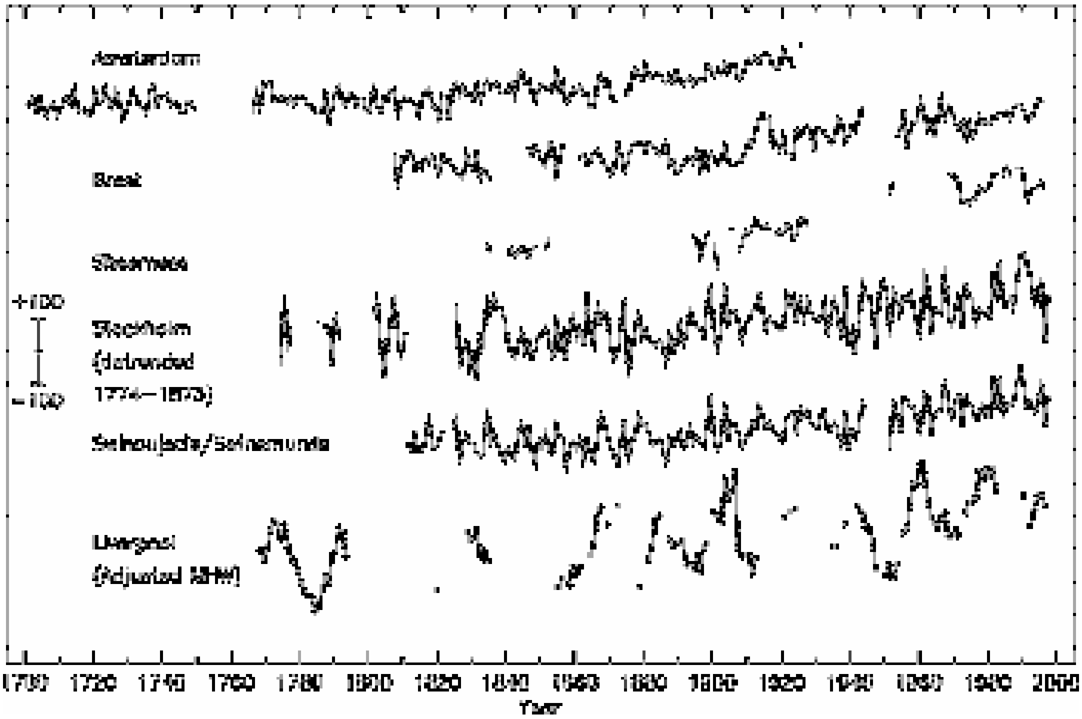


Figure 6.1: Time-series of Relative Sea Level for the past 300 years from Northern Europe (IPCC, 2001 Figure 11.7).

Notes: The scale bar indicates ±100 mm.

6.2.2 Satellite Altimetry

On 10 August 1992, NASA and the French National Space Agency launched the TOPEX/Poseidon Satellite into space with the aim of using satellite altimeters to amongst other things, improve understanding of ocean currents and accurately measure the surface of the ocean. The satellite has a 10 day repeat of the ground track covering 95% of the ice-free oceans with sea level measurement accuracy to better than 50mm (NASA JPL, 2008).

On 7 December 2001, joint partners NASA and the French National Space Agency launched the Jason-1 satellite to continue the task of providing oceanographic time series data originated by the TOPEX/Poseidon, carrying updated versions of the same instrumentation with an improved ocean surface measuring accuracy to 33mm. The Jason-1 satellite flies in tandem with the TOPEX/Poseidon enabling direct calibration between satellites. A further mission, the OSTM/Jason-2 satellite altimeter was launched on 20 June 2008 to extend the work of the existing missions and seek an ocean water level measuring accuracy to 25mm (NASA JPL, 2008).

Both longer-term missions have provided greatly enhanced measurements of the ocean water surface for direct correlation to the many land based tide gauges around the earth. The use of satellite altimetry to measure changes in the global average sea surface, avoids land surface movements which encumber standard land based tide gauge facilities.

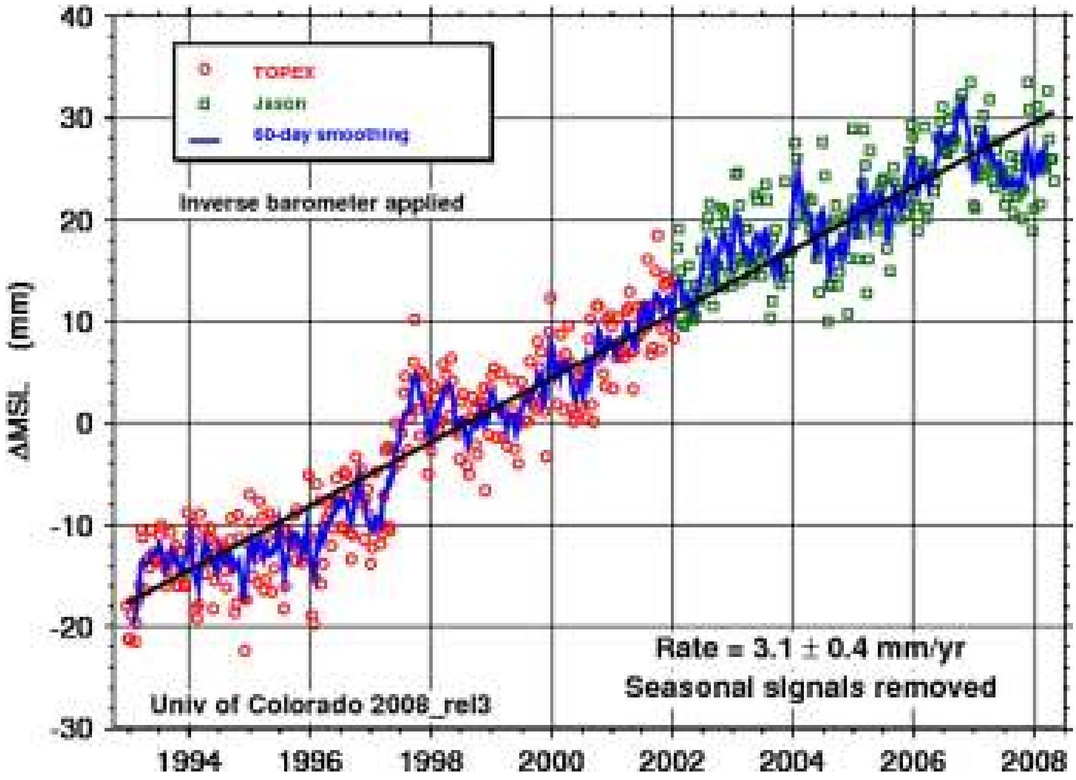


Figure 6.2: Measured Change in Mean Sea Level from Satellite Altimetry

Notes:
1. Data period: 6 December 1992 to 28 April 2008.
2. Data analyses removes barometric effects and seasonal signals.
3. Source: University of Colorado at Boulder (2008).

Over the operation of the TOPEX/Poseidon and Jason-1 missions, there has been a measured increase in global average sea level of approximately 3.1 ± 0.4 mm/yr (refer Figure 6.2). Although the satellite altimeters provide improved accuracies for global sea level rise monitoring, the increased rate of sea level rise evident between 1993 and present has been measured over a relatively short period and could yet prove to be a function of inter-decadal variability which is evident in the longer term tidal gauge records worldwide (refer Figure 6.1). Nonetheless, when the altimeter data is synthesized with the longer-term tidal gauge records (refer Figure 6.3), there is a clear evidentiary trend of measured, increasing (albeit at low rates of) sea level rise.

Around the time the initial TOPEX/Poseidon satellite was launched in 1992, the Australian Baseline Sea Level Monitoring Project (ABSLMP) commenced. The project involves 16 “SEAFRAME” stations spread around the Australian coastline and managed by the National Tidal Centre to monitor sea level and climate over the long term. The SEAFRAME stations have provided important ‘ground-truth’ sea level data for calibration and validation of the satellite altimeters. In shallow coastal waters satellite altimeter measurements are inaccurate and tide gauges are a necessity not only for monitoring long-term sea levels but also extreme events (NTC, 2007).

The SEAFRAME stations also contribute to the Global Sea Level Observing System (GLOSS) under the auspices of the World Meteorological Organisation (WMO) and Intergovernmental Oceanographic Commission (IOC).

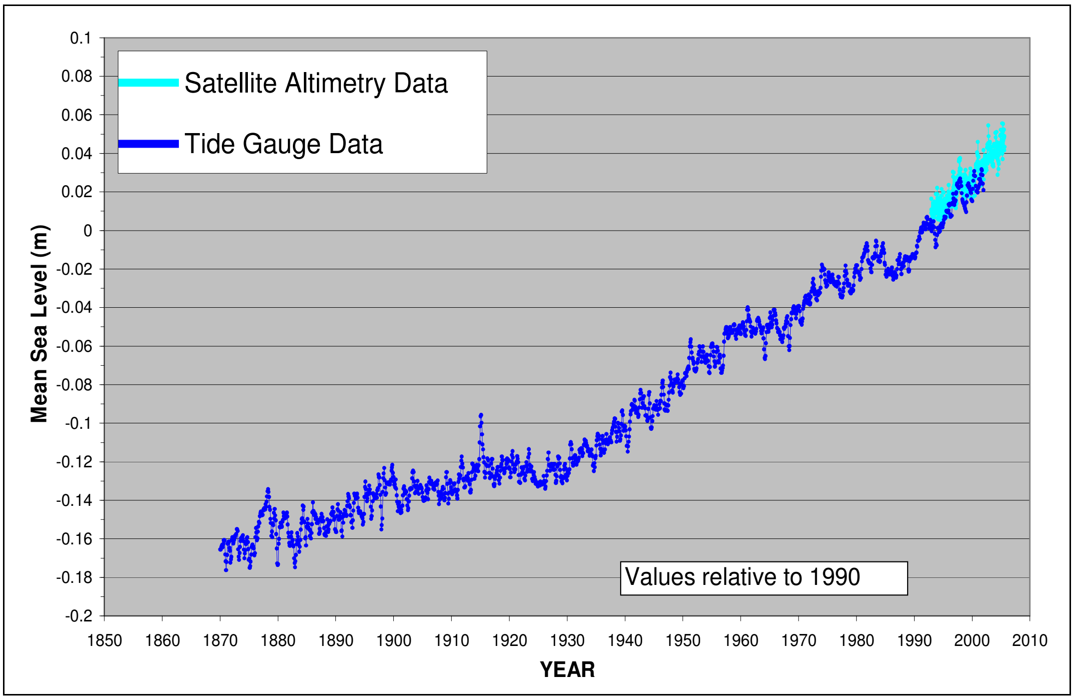


Figure 6.3: Measured Global Averaged Mean Sea Level since 1870

Notes:
1. Tide gauge data from Church and White (2006).
2. Satellite altimetry data from Leuliette et al (2004).

6.3 Projected Sea Level Rise

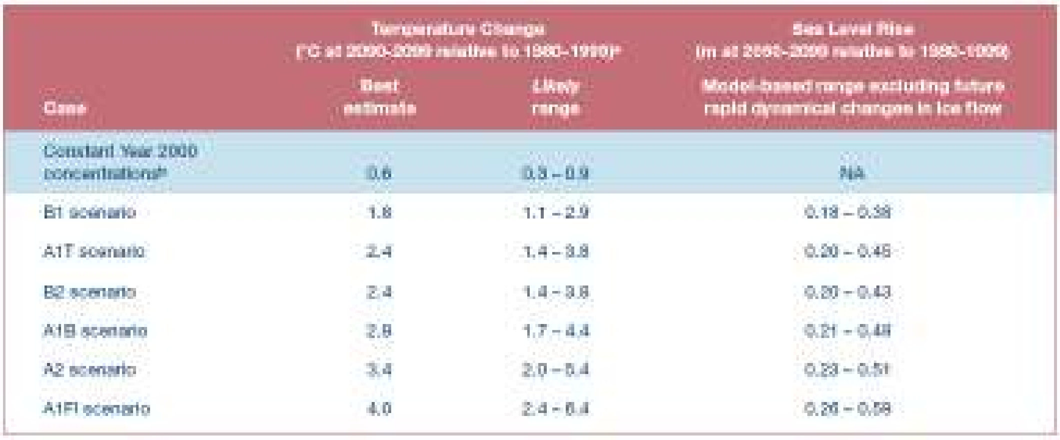
IPCC (2007) provides an up to date appraisal of international literature and scientific advancements in the area of climate change induced sea level rise and modelling of future emission scenarios.

IPCC (2007) advises projected global average sea level rise over the 21st century from various modelled emission scenarios are predicted to range from 18 to 59cm (at 2090-2099 relative to 1980-1999, refer Table 6.1). A further allowance of 10 to 20cm is advised for the upper range of sea level rise scenarios in the event that ice sheet flow rates increase linearly with global average temperature change. The emission scenarios modelled are standardised scenarios developed in 1992 by the IPCC which broadly correspond to differing world socio-economic and population regimes in the future.

IPCC (2007) advise that whilst there will be a projected rise in global average sea level, there will be considerable regional variability in the rate of sea level rise due to the differential capacity of the oceans of the earth to distribute heat energy. The strength of the East Australian Current (EAC) is expected to result in greater efficiency to transfer heat energy through the Southern Pacific Ocean. Recent modelling undertaken by CSIRO (2007) indicates the ocean water levels off the NSW coastline could be of the order of 0-8cm and 0-12cm higher than the global average by 2030 and 2070, respectively.

IPCC (2007) continues to build on the reliability of previous sea level rise projections through improved understanding of complex governing ocean-atmosphere relationships, improved understanding of global water budgets, greater diversity and capacity of mathematical models and synthesis of longer and improved measured data from integrated tide gauge networks and satellite altimetry.

Table 6.1: Projected Sea Level Rise (IPCC, 2007)



Case	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Despite the improved reliability of the IPCC (2007) sea level rise projections, there remains some concern that the sum of the 7 primary components (refer Section 6.1) in the budget determined to comprise sea level rise remains less than the measured rate of sea level rise through both the 2001 and 2007 IPCC assessment reports. For the period from 1961-2003 the difference in the budget was estimated at 0.7 ± 0.7 mm/yr. For the period from 1993 to 2003 the sum of the respective components of sea level rise is still less than the measured rate by some 0.3 ± 1.0mm/yr. This indicates there has been progress in understanding sea level rise mechanisms from the 2001 report, primarily due to improved knowledge of individual terms and the availability of the satellite altimetry (IPCC, 2007).

Although the international scientific community are continuing to improve knowledge on climate change impacts and predictions, the understanding of all the complex interrelated climatological, atmospheric and oceanographic processes remains incomplete. The sea level projections in IPCC 2007 were based on a mid-estimate rise of 1.8mm/year. Current satellite altimetry measurements from 1992 to present indicate measured sea level rise over this period at approximately 3.1 ± 0.4mm/yr, in line with the upper bound IPCC (2007) model predictions.

IPCC (2007) advise that sea level rise under global warming is inevitable. Thermal expansion would continue for many centuries after greenhouse gas concentrations have stabilised, for any of the CO_2 emission scenarios assessed, causing an eventual sea level rise much larger than projected for the 21st century (advised in Table 6.1). The eventual contributions from Greenland ice sheet loss could be several metres (and larger than from thermal expansion), should warming in excess of 1.9 to 4.6℃ above pre-industrial levels be sustained over many centuries (IPCC, 2007). The long time scales of thermal expansion and ice sheet response to warming imply that stabilisation of greenhouse gas concentrations at or above present levels would not stabilise sea level for many centuries (IPCC, 2007).

IPCC (2007) does not provide sea level rise estimates for intermediate timeframes (prior to 2090-2099). IPCC (2001) however, provided graphical timescale representations of sea level rise to 2100 which have been used to provide indicative sea level rise estimates for 2050. This is a reasonable approach given that IPCC (2007) advises that for each emission scenario modelled (see Table 6.1), the midpoint is within 10% of the IPCC 2001 model average for 2090 to 2099.

Table 6.2 summarises appropriate allowances for vulnerability assessments relevant to various planning horizons (2050, 2100) based on a synthesis of all information on projected sea level rise currently available.

Table 6.2: Advised Sea Level Rise Estimates for Various Planning Horizons

Sea Level Rise Scenario	YEAR 2050	YEAR 2100
Lower Bound Estimate (**LOW**)	4 cm (1)	16 cm (3)
Medium Estimate (**MED**) (5)	21 cm	53 cm
Upper Bound Estimate (**HIGH**)	38 cm (2)	89 cm (4)

Notes:
1. SLR estimate derived from Figure 11.12 (IPCC, 2001) corrected for application from 2008.
2. SLR estimates derived from Figure 11.12 (IPCC, 2001) corrected for application from 2008 (26cm) with the addition of 12 cm to account for the upper bound regional increase in SLR above the global average (CSIRO, 2007).
3. SLR estimate from Table SPM.3 (IPCC, 2007) using the 18cm advised, corrected for application from 2008 assuming average increase in MSL of 1.8mm/year from 1999.
4. SLR estimate from Table SPM.3 (IPCC, 2007) using the 59cm advised, corrected for application from 2008 assuming average increase in MSL of 1.8mm/year from 1999. An additional 20cm has been added to account for the possibility of ice sheet flow rates increasing linearly with increased temperature for upper bound projections as advised by IPCC (2007). A further 12cm has been added to account for the upper bound regional increase in SLR above the global average (CSIRO, 2007).
5. Medium position between “lower” and “upper” bound derived estimates rounded up to nearest cm.

6.4 Design Still Water Levels (Incorporating Sea Level Rise)

Still water levels determined from the extreme value analysis of the continuous water level recording data from Fort Denison (refer Section 5.4.6), have been synthesised with the respective sea level rise estimates in Table 6.2 to provide design still water levels incorporating sea level rise for various planning horizons (refer Table 6.3).

Figures 6.4 and 6.5 graphically illustrate the indicative recurrence of various water levels under future sea level rise scenarios for 2050 and 2100 relative to the present, respectively.

Table 6.3: Sydney Harbour Design Still Water Levels for Future Planning Horizons (Incorporating Sea Level Rise)

ARI (Years)	2008 Design Still Water Levels (m AHD)	SLR Scenario (L, M, H)	2050 Design Still Water Levels (m AHD)	2100 Design Still Water Levels (m AHD)
0.02	0.965	L	1.005	1.125
		M	1.175	1.495
		H	1.345	1.855
0.05	1.045	L	1.085	1.205
		M	1.255	1.575
		H	1.425	1.935
0.10	1.095	L	1.135	1.255
		M	1.305	1.625
		H	1.475	1.985
1	1.235	L	1.275	1.395
		M	1.445	1.765
		H	1.615	2.125
2	1.275	L	1.315	1.435
		M	1.485	1.805
		H	1.655	2.165
5	1.315	L	1.355	1.475
		M	1.525	1.845
		H	1.695	2.205
10	1.345	L	1.385	1.505
		M	1.555	1.875
		H	1.725	2.235
20	1.375	L	1.415	1.535
		M	1.585	1.905
		H	1.755	2.265
50	1.415	L	1.455	1.575
		M	1.625	1.945
		H	1.795	2.305
100	1.435	L	1.475	1.595
		M	1.645	1.965
		H	1.815	2.325

Notes:
1. 2008 design still water levels derived from Table 5.3 (Section 5.4.6).
2. L, M and H refer to Low, Medium and High projections for sea level rise. Corresponding allowances derived from Table 6.2.

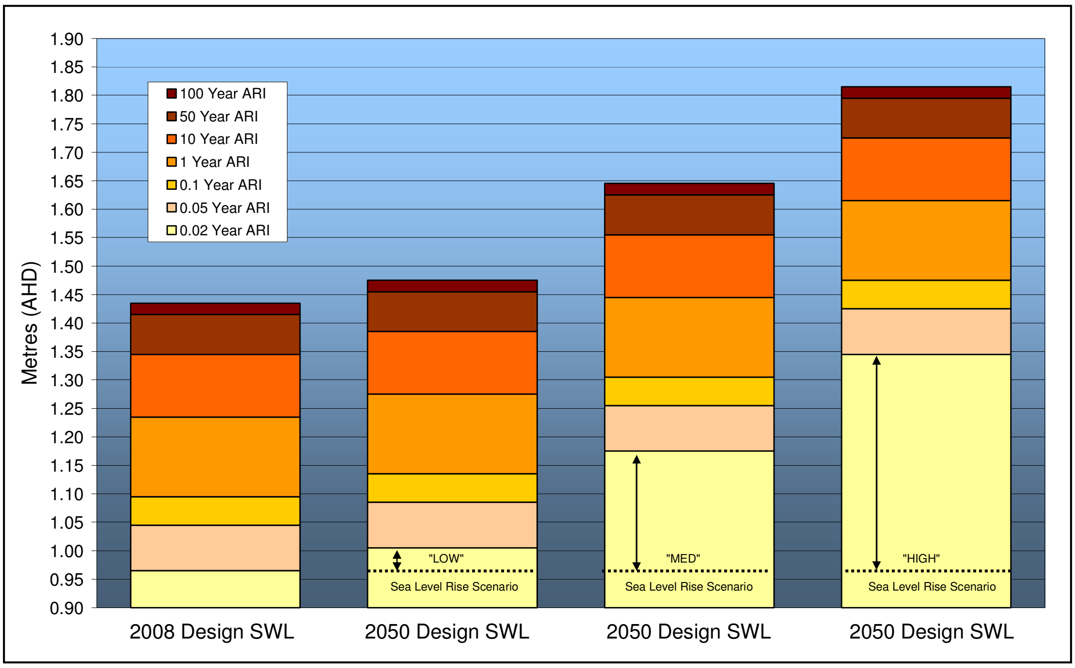


Figure 6.4: Projected 2050 Design Still Water Levels

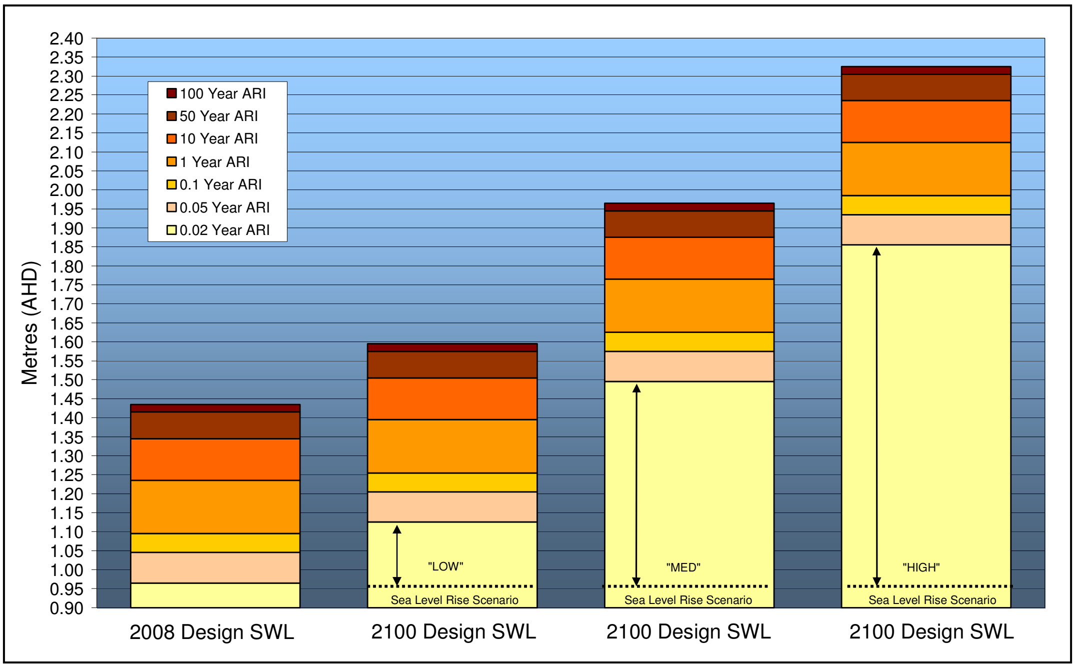


Figure 6.5: Projected 2100 Design Still Water Levels

6.5 Design Wave Runup Levels (Incorporating Sea Level Rise)

The actual runup from waves is a relatively dynamic and highly variable phenomena which is usually expressed as a height measured vertically above the still water level (R_u), exceeded by a small percentage of waves. Various approaches are available for determining the $R_{u2\%}$ which relates to the runup height exceeded by 2% of incident waves and is commonly used for design purposes.

Appendix E summarises a detailed assessment of design wave runup levels ($R_{u2\%}$) based upon the application of the design wave climate comprising a combination of wind and boat waves (refer Appendix D). Table 6.4 summarises design 100 year ARI wave runup levels for various planning horizons, incorporating projected sea level rise estimates.

Table 6.4: Fort Denison Design Wave Runup Levels ($R_{u2\%}$)

Location	Timeframe	Water Levels			Wave Conditions		Design Runup Level
		ARI	SLR Scenario (L,M,H)	Design SWL (m AHD)	Hsig (m)	Tsig (s)	$R_{u2\%}$ + Design SWL (m AHD)
A (Western Seawall)	2008	100	NA	1.435	1.19	1.4	5.24
	2050		L	1.475			5.28
			M	1.645			5.45
			H	1.815			5.62
	2100		L	1.595			5.40
			M	1.965			5.77
			H	2.325			6.13
B (Slipyard/ BBQ Area)	2008	100	NA	1.435	1.15	1.6	5.12
	2050		L	1.475			5.16
			M	1.645			5.33
			H	1.815			5.50
	2100		L	1.595			5.28
			M	1.965			5.65
			H	2.325			6.01
C (Eastern Seawall)	2008	100	NA	1.435	1.10	1.9	4.96
	2050		L	1.475			5.00
			M	1.645			5.17
			H	1.815			5.34
	2100		L	1.595			5.12
			M	1.965			5.49
			H	2.325			5.85
D (Tide Room)	2008	100	NA	1.435	1.14	1.5	5.08
	2050		L	1.475			5.12
			M	1.645			5.29
			H	1.815			5.46
	2100		L	1.595			5.24
			M	1.965			5.61
			H	2.325			5.97

Notes:
1. Design wave runup locations indicated in Figure E3, (Appendix E).
2. Design wave runup levels derived from Appendix E and rounded up to two decimal places.
3. Only the limiting design "equivalent" wave condition is indicated above (ie. the wave condition producing the highest 2% wave runup level).
4. Design still water levels incorporating projected "H", M" or "L" sea level rise projections derived from Table 6.3.
5. All relevant levels based on Australian Height Datum (AHD).

6.6 Discussion

It is recognised that the Average Recurrence Interval (ARI) ascribed to the design still water levels used in this report have been based on current analyses (2008) and have been simply assumed to be relevant in 2050 and 2100 with the addition of the projected sea level rise estimates. As such, the design ARI's for 2050 and 2100 presented in Table 6.3 are provided as an indicative guide only.

For example in 2050, it is estimated that under a "MEDIUM" sea level rise scenario (16cm), the hourly water level reached some 50 times per year would be equivalent to that reached currently on only 3 occasions per year. Similarly, for the same sea level rise scenario, the hourly water level reached on average once per year in 2050 would exceed the current 100 year ARI water level.

Under a "HIGH" sea level rise scenario (38cm), the hourly water level predicted to be reached on some 50 occasions per year in 2050 equates to a current water level with an ARI of 10 years. Similarly under the same sea level rise scenario, the predicted hourly water level that will be reached on some 10 occasions per year equates to the highest water level recorded at Fort Denison (1.475m AHD on 25 May 1974) between 1914 and the present.

For 2100, under a "MEDIUM" sea level rise scenario (53cm), the hourly water level projected to be reached on 50 occasions per year would exceed the highest water level recorded at Fort Denison. Similarly, under a "HIGH" sea level rise scenario (89cm), the hourly water level reached on 50 occasions per year in 2100 would be approximately 42cm higher than the current 100 year ARI water level.

7 VULNERABILITY ASSESSMENT

The vulnerability assessment is primarily based on comparing current and future design still water and wave runup levels (incorporating sea level rise) with the existing level of infrastructure and assets on Fort Denison. For example, the crest level of the external walls of the Fort, decks and floor levels, all provide direct references to assess the likelihood or extent of overtopping and inundation expected due to particular sea level rise scenarios over various future planning horizons.

The vulnerability assessment of Fort Denison to climate change induced sea level rise has been based on three separate planning horizons, namely present day (2008), 2050 and 2100. Design still water levels of varying Average Recurrence Interval (0.02 to 100 years) have been considered along with “LOW”, “MEDIUM” and “HIGH” projected sea level rise scenarios. These design still water levels have been coupled with an “equivalent” or representative design wave climate to estimate wave runup ($R_{u2\%}$) levels around the periphery of the Fort for each planning horizon.

The design still water level represents the peak water level in the absence of waves. The $R_{u2\%}$ represents the runup level reached by 2% of the design wave climate superimposed on the design still water level. It should be understood that the wave generation source can produce distinctly different waves. Wind generated wave fields around Fort Denison can prevail for as long as the driving wind force persists (which can be several hours). Conversely, boat generated waves are created by a moving vessel pushing water out from the hull as it is propelled forward. The wave generation force therefore is a moving one and substantive boat generated wave fields generally do not persist at a given location for longer than a minute.

The design wave climate (refer Appendix D) is based on assimilating both the wind and boat wave influences. The process is dominated by the largest (or limiting) boat wave measured on Sydney Harbour, as this is larger than any of the hindcast wind waves approaching Fort Denison. The design wave climate used for this study is therefore considered a reasonably conservative (or upper bound) condition for determining design wave forces and runup levels (refer Appendix E) on foreshores and structures at this location, in the absence of long-term measured wave data.

The design runup levels advised provide an indicative estimate of the height to which seawater may rise after breaking against the near vertical external stone seawalls around the Fort. Generally the majority of the wave action will be reflected from the vertical seawalls, however, direct overtopping would be expected when the waves are accompanied by a following wind.

7.1 Present Day Planning Horizon (2008)

The entry to the Western Terrace via the wharf is elevated at 1.41m AHD and is the lowest point (and therefore the most vulnerable area) for direct ingress of seawater around Fort Denison. This entry point is vulnerable to tidal inundation by seawater with an Average Recurrence Interval (ARI) of 50 years or more, in the absence of wave action (refer Table 7.1).

The current design 100 year ARI still water level (1.435m AHD) is sufficient to cover the lowest surveyed point on the Western Terrace (1.34m AHD) forecourt by up to 95mm of seawater for possibly 30-60 minutes but would not enter doorway sill levels entering to the forecourt from the Barracks. Nonetheless, sub-flooring structures supporting the floorboards within the Barracks would be expected to be submerged by water levels with a more modest recurrence interval.

Figure 7.1: Entry to Western Terrace

The floor of the Magazine Room within the Martello Tower is elevated at approximately 1.23m AHD which corresponds to a still water level with an ARI of around 1 year. If the periphery of the Martello Tower was not sufficiently maintained to prevent seawater penetration to the Magazine Room then a small amount of seepage could be expected on roughly a per annum basis.

The lowest crested seawall structures around Fort Denison are the Western Seawall (2.67 – 2.79m AHD) and the curvilinear wall around the Slipyard/BBQ area (2.84m AHD). Both walls are exceeded by the 100 year ARI design wave runup level by 2.57 and 2.28m, respectively. Notwithstanding, both walls are elevated above the crest of the incoming design wave fields for a 100 year ARI still water level. No other external walls are currently considered vulnerable to the 100 year ARI design wave runup level.

7.2 2050 Planning Horizon

The postulated "LOW" (4cm), "MEDIUM" (21cm) and "HIGH" (38cm) sea level rise scenarios for 2050 elevate the design still water and wave runup levels accordingly. Under a 'LOW" sea level rise scenario the entry point to the "Western Terrace" forecourt area is vulnerable to tidal inundation by seawater with an ARI of 50 years or more, in the absence of wave action (refer Table 7.2). However under a "HIGH" sea level rise scenario, the entry point is predicted to be vulnerable to tidal inundation by seawater where the hourly water level would be reached as often as 20 times per year.

The projected 2050 design 100 year ARI still water level ranges from 1.475 to 1.815m AHD and depending on the sea level rise scenario considered, this could be sufficient to cover the lowest surveyed point on the Western Terrace (1.34m AHD) forecourt by between 13 and 48cm with seawater. Similarly, several floors within the "Barracks" could be expected to be submerged to varying levels within this range depending on the still water level ARI and sea level rise scenario (refer Table 7.2).

Figure 7.2: Western Terrace forecourt

Under a "LOW" sea level rise scenario, the floor of the Magazine Room within the Martello Tower would be at a level below a design still water level with an ARI slightly less than a year. However, under a "HIGH" sea level rise scenario, the floor of the "magazine room" would similarly be below a design still water level where the hourly water level would be reached as often as 50 times per year.

The crest of the Western Seawall (2.67 – 2.79m AHD) and the curvilinear wall around the Slipyard/BBQ area (2.84m AHD) are elevated below the 100 year ARI design wave runup height by between 2.61 and 2.95m and 2.32 and 2.66m, respectively, depending on the sea level rise scenario. Both walls are elevated above the crest of the incoming design wave fields for a 100 year ARI still water level under a "HIGH" sea level rise scenario.

No other external walls are currently considered vulnerable to the 100 year ARI design wave runup level.

7.3 2100 Planning Horizon

The postulated “LOW” (16cm), “MEDIUM” (53cm) and “HIGH” (89cm) sea level rise scenarios for 2100 elevate the design still water and wave runup levels, accordingly. Under a “LOW” sea level rise scenario the entry point to the “western terrace” is vulnerable to tidal inundation by ocean waters with an ARI of 10 years or more, in the absence of wave action (refer Table 7.3). However under a “HIGH” sea level rise scenario, the entry point is predicted to be vulnerable to tidal inundation by ocean waters where the hourly water level would be reached as often as 50 times per year.

The projected 2100 design 100 year ARI still water level ranges from 1.595 to 2.325m AHD and would be sufficient to cover the lowest surveyed point on the “Western Terrace” (1.34m AHD) forecourt by between 25 and 99cm with seawater. Under the “HIGH” scenario, the 100 year ARI design still water level would be a mere 34.5cm below the crest of the north-western seawall at its lowest point. Similarly, all floors within the Barracks could be expected to be submerged to varying levels within this range depending on the still water level ARI and sea level rise scenario (refer Table 7.3). Under a “HIGH” sea level rise scenario, the 100 year ARI still water level would be some 80cm above the lowest floor level in the Barracks.

Excluding the Martello Tower, the 100 year ARI design wave runup level would exceed the crest level of all structures, for all sea level rise scenarios, with the exception of the “Eastern Seawall” which would only be exceeded under a “HIGH” scenario.

Both the top of the Western Seawall (2.67 – 2.79m AHD) and the curvilinear wall around the Slipyard/BBQ area (2.84m AHD) are elevated **below** the crest of the incoming design wave fields for a 100 year ARI still water level under a “HIGH” sea level rise scenario.

Figure 7.3: Western Seawall

Table 7.1: Assets currently vulnerable to oceanic inundation (2008)

		Feature																					
Average Recurrence Interval (Years)[1]	Sea Level Rise Scenario (H, M, L)[2]	Floor of Tide Room (1.78m AHD)	Floor of Kitchen Storage Room (1.68m AHD)	Floor of Kitchen (1.58m AHD)	Floor of Restaurant (1.54m AHD)	Floor of Museum (1.63m AHD)	Floor of Amenities (Ladies) (1.58m AHD)	Floor of Amenities (Gents) (1.61m AHD)	Floor of Entry to Eastern Terrace (1.53m AHD)	Bitumen forecourt of Western Terrace (1.34 – 1.48m AHD)	Entry to Western Terrace (1.41m AHD)	Floor at Entry to Martello Tower (3.54m AHD)	Floor in Martello Tower (Gunpowder Room) (1.23m AHD)	Floor in Martello Tower (Cannon Room) (6.89m AHD)	Crest of Western Seawall (2.67 – 2.79m AHD)	Natural surface of Slipyard/BBQ Area (1.73 – 1.97m AHD)	Crest of linear seawall around BBQ facility (3.49 – 3.60m AHD)	Crest of curvilinear seawall around Slipyard/BBQ area (2.84m AHD)	Top of curvilinear perimeter wall around Bastion (5.21 – 5.30m AHD)	Grassed Eastern Terrace (3.65 – 3.94m AHD)	Entry to Martello Tower (3.54m AHD)	Crest of Eastern Seawall (5.57 – 5.62m AHD)	Top of Martello Tower (15.38m AHD)
0.02	NA																						
0.05	NA																						
0.1	NA																						
1	NA												■										
10	NA												■										
50	NA									■	■		■										
100	NA									■	■		■										

Notes:
1. Design still water levels for respective ARIs derived from Table 5.3.
2. Design still water levels incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 6.2 and 6.3.
3. Assets deemed vulnerable when respective design still water level exceeds height of asset.
4. Where an asset has a variable height, the lowest elevation has been used to assess vulnerability.
5. Refer Figure 2.2 for location of relevant features.

Table 7.2: Assets deemed vulnerable to oceanic inundation in 2050 (incorporating allowances for projected mean sea level rise)

		Feature																					
Average Recurrence Interval (Years) [1]	**Sea Level Rise Scenario (H, M, L)** [2]	Floor of Tide Room (1.78m AHD)	Floor of Kitchen Storage Room (1.68m AHD)	Floor of Kitchen (1.58m AHD)	Floor of Restaurant (1.54m AHD)	Floor of Museum (1.63m AHD)	Floor of Amenities (Ladies) (1.58m AHD)	Floor of Amenities (Gents) (1.61m AHD)	Floor of Entry to Eastern Terrace (1.53m AHD)	Bitumen forecourt of Western Terrace (1.34 – 1.48m AHD)	Entry to Western Terrace (1.41m AHD)	Floor at Entry to Martello Tower (3.54m AHD)	Floor in Martello Tower (Gunpowder Room) (1.23m AHD)	Floor in Martello Tower (Cannon Room) (6.89m AHD)	Crest of Western Seawall (2.67 – 2.79m AHD)	Natural surface of Slipyard/BBQ Area (1.73 – 1.97m AHD)	Crest of linear seawall around BBQ facility (3.49 – 3.60m AHD)	Crest of curvilinear seawall around Slipyard/BBQ area (2.84m AHD)	Top of curvilinear perimeter wall around Bastion (5.21 – 5.30m AHD)	Grassed Eastern Terrace (3.65 – 3.94m AHD)	Entry to Martello Tower (3.54m AHD)	Crest of Eastern Seawall (5.57 – 5.62m AHD)	Top of Martello Tower (15.38m AHD)
0.02	L																						
	M																						
	H												■										
0.05	L																						
	M												■										
	H									■	■		■										
0.1	L																						
	M												■										
	H									■	■		■										
1	L												■										
	M									■	■		■										
	H			■	■		■	■	■	■	■		■										
10	L												■										
	M				■				■	■	■		■										
	H		■	■	■	■	■	■	■	■	■		■										
50	L									■	■		■										
	M			■	■		■	■	■	■	■		■										
	H	■	■	■	■	■	■	■	■	■	■		■			■							
100	L									■	■		■										
	M			■	■	■	■	■	■	■	■		■										
	H	■	■	■	■	■	■	■	■	■	■		■			■							

Notes:
1. Design still water levels for respective ARIs derived from Table 5.3.
2. Design still water levels incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 6.2 and 6.3.
3. Assets deemed vulnerable when respective design still water level exceeds height of asset.
4. Where an asset has a variable height, the lowest elevation has been used to assess vulnerability.
5. Refer Figure 2.2 for location of relevant features.

Table 7.3: Assets deemed vulnerable to oceanic inundation in 2100 (incorporating allowances for projected mean sea level rise)

		Feature																					
Average Recurrence Interval (Years) [1]	**Sea Level Rise Scenario (H, M, L)** [2]	Floor of Tide Room (1.78m AHD)	Floor of Kitchen Storage Room (1.68m AHD)	Floor of Kitchen (1.58m AHD)	Floor of Restaurant (1.54m AHD)	Floor of Museum (1.63m AHD)	Floor of Amenities (Ladies) (1.58m AHD)	Floor of Amenities (Gents) (1.61m AHD)	Floor of Entry to Eastern Terrace (1.53m AHD)	Bitumen forecourt of Western Terrace (1.34 – 1.48m AHD)	Entry to Western Terrace (1.41m AHD)	Floor at Entry to Martello Tower (3.54m AHD)	Floor in Martello Tower (Gunpowder Room) (1.23m AHD)	Floor in Martello Tower (Cannon Room) (6.89m AHD)	Crest of Western Seawall (2.67 – 2.79m AHD)	Natural surface of Slipyard/BBQ Area (1.73 – 1.97m AHD)	Crest of linear seawall around BBQ facility (3.49 – 3.60m AHD)	Crest of curvilinear seawall around Slipyard/BBQ area (2.84m AHD)	Top of curvilinear perimeter wall around Bastion (5.21 – 5.30m AHD)	Grassed Eastern Terrace (3.65 – 3.94m AHD)	Entry to Martello Tower (3.54m AHD)	Crest of Eastern Seawall (5.57 – 5.62m AHD)	Top of Martello Tower (15.38m AHD)
0.02	L																						
	M									■	■		■										
	H	■	■	■	■	■	■	■	■	■	■		■			■							
0.05	L												■										
	M				■				■	■	■		■										
	H	■	■	■	■	■	■	■	■	■	■		■			■							
0.1	L												■										
	M			■	■		■	■	■	■	■		■										
	H	■	■	■	■	■	■	■	■	■	■		■			■							
1	L												■										
	M		■	■	■	■	■	■	■	■	■		■			■							
	H	■	■	■	■	■	■	■	■	■	■		■			■							
10	L									■	■		■										
	M	■	■	■	■	■	■	■	■	■	■		■			■							
	H	■	■	■	■	■	■	■	■	■	■		■			■							
50	L				■				■	■	■		■										
	M	■	■	■	■	■	■	■	■	■	■		■			■							
	H	■	■	■	■	■	■	■	■	■	■		■			■							
100	L			■	■		■		■	■	■		■										
	M	■	■	■	■	■	■	■	■	■	■		■			■							
	H	■	■	■	■	■	■	■	■	■	■		■			■							

Notes:
1. Design still water levels for respective ARIs derived from Table 5.3.
2. Design still water levels incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 6.2 and 6.3.
3. Assets deemed vulnerable when respective design still water level exceeds height of asset.
4. Where an asset has a variable height, the lowest elevation has been used to assess vulnerability.
5. Refer Figure 2.2 for location of relevant features.

8 CONCLUSIONS

The vulnerability assessment is based upon the most authoritative, currently available information concerning climate change induced sea level rise and how it will impact upon Fort Denison over various planning horizons.

At present, the best available information suggests that sea level rise in Sydney Harbour due to climate change could range from 4-38cm and 16-89cm by 2050 and 2100, respectively. The most accurate measured sea level rise data from satellite altimetry dating back to late 1992, indicates global sea level rising during this period at approximately 3.1mm/year. Although this is only a relatively short record, these rates equate to the upper limit trajectory for modelled sea level rise over the 21st century as projected by the Inter-governmental Panel on Climate Change (2001 and 2007).

Surrounded by the tidal waters of Sydney Harbour, it is clear that Fort Denison is particularly vulnerable to any form of sea level rise. Elevated at a mere 1.41m AHD, the entry through the Western Seawall to the forecourt area known as the Western Terrace, is the most obvious and vulnerable point of ingress for seawater. The highest recorded water level at Fort Denison (since 1914) was 1.475m AHD on 25 May 1974, some 65mm higher than the current entry point to the Fort.

Clearly upper bound sea level rises of the magnitude advised to 2050 and 2100 would have a profound inundation impact upon the site as it is currently configured. For example, under a “HIGH” sea level rise scenario in 2100, it is estimated that the entry forecourt would be submerged at least 15% of the time by seawater. The depth of submergence could be as much as 45cm by common hourly water levels that would be reached on approximately 50 occasions per year. Even if the entry to the forecourt area were removed and replaced with a continuous Western Seawall, seepage through the foundations of the Fort is extensive and evident under the sub-flooring beneath the Barracks (refer Figure 8.1).

The lowest floor level is the Magazine Room in the Martello Tower at 1.23m AHD. Clearly any seepage of seawater through the periphery of the Martello Tower to this area will have an increasingly profound impact over time given the projections for sea level rise.

In addition to the threat from inundation due to still water levels, wave climates discharge energy against the external vertical walls of the Fort resulting in seawater being elevated up the face of the wall to significant heights. The lower crested Western Seawall and curvilinear wall around the Slipyard/BBQ area are currently exceeded by 100 year ARI design wave runup levels by in excess of 2.2m. Considering the projections for future sea level rise, these structures will become increasingly more vulnerable to wave runup and overtopping over time.

It should be recognised that the governing factor in establishing a design wave climate for Fort Denison is that of boat waves. The largest boat wave measured from a range of previous studies is larger than any of the hindcast wind waves for Fort Denison. Thus the design wave climate is substantially based upon a relative conservative application of limited published information on measured boat waves in Sydney Harbour. Direct measured boat and wind wave data around Fort Denison would provide a more rigorous assessment of design wave climates and associated runup and overtopping levels.

It is likely that the current configuration of the Fort could continue to be effectively managed with minor modifications (raising floor levels where necessary to combat a modest rise in sea level of possibly 10-20cm).

Figure 8.1: Existing seawater ingress below flooring system (approx 1.90m ISLW)

However, inundation from sea water due to larger sea level rises will substantially compromise the useability and general accessibility of the site as well as the maintenance of the built heritage assets, flooring systems, etc. Under these circumstances significant alterations may be necessary to continue use of the site whilst accommodating a mean sea level rise of up to 1m. These alterations would include: blocking up the existing entry point with a continuous Western Seawall, sealing the foundations and external blockwork to prevent seepage and direct ingress of seawater and consideration of increasing the crest of existing seawalls or introducing wave deflector capping to limit potential wave runup and overtopping from entering the site.

It is important to appreciate that sea level rise is projected to increase on an increasing trajectory, well beyond the conventional planning horizon of 2100. Under these circumstances, and in the absence of substantial changes to the integrity of the current built form, Fort Denison will become a successively submerged artefact over an indeterminate timeframe, well into the future.

Similarly, it is important to recognise that although every effort has been made to provide the most up to date advice within this report on climate change induced sea level rise, projections of sea level rise over longer term planning horizons are uncertain and continually evolving and will be driven by global socio-political climate change policy, continued advancements with climate change modelling and success in limiting greenhouse gas emissions.

In the interim, future planning at Fort Denison, which is particularly vulnerable to climate change induced sea level rise can be guided by the implications of the advice contained within this report and updated at not more than 10 yearly intervals in order to stay abreast of advancements regarding both the monitoring and projections of this significant phenomenon.

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10 REFERENCES

1. Bureau of Meteorology website (BoM, 2008). www.bom.gov.au
2. Blumberg, G.P, (1991). *Pers Comms*, Referenced in Willoughby (1991).
3. Church, J.A and White, N.J (2006). *"A 20th Century Acceleration in Global Sea Level Rise"*. Geophysical research letters, Vol 33, L01602, doi:10.1029/2005GL024826.
4. Cox, R.J and Blumberg, G.P, (1984). *"Opera House Covered Walkway – Marine Hydraulic Studies"*, University of NSW Water Research Laboratory, Technical Report No. 84/16.
5. CSIRO (2007). *"Projected Changes in Climatological Forcing for Coastal Erosion in NSW".* A Project undertaken for the NSW Department of Environment and Climate Change, August.
6. Edwards, S and Lord, D.B (1998). *"Boat Waves and their Effect on the Shoreline of NSW Harbours and Inlets"*, Proceedings of the 8th Annual NSW Coastal Conference, Batemans Bay, 10-13 November.
7. EurOtop (2007). *"Wave Overtopping of Sea Defences and Related Structures: Assessment Manual"*, Produced by Environmental Agency (UK), Coastal Engineering Research Council (Germany) and Rijkswaterstaat (Netherlands), August.
8. Glamore, W.C and Badenhop, A, (2007). *"Managing and Assessing Boat Wake Waves"*, Proceedings of the 18th Australasian Coastal and Ocean Engineering Conference, Melbourne, July.
9. Glamore, W (2008). *"A Decision Support Tool for Assessing the Impact of Boat Wake Waves on Inland Waterways"*, On-Course, PIANC, pp 5-18, October.
10. Hamon, B.V (1987). *"A Century of Tide Records: Sydney (Fort Denison) 1886-1986"*, Flinders Institute for Atmospheric and Marine Sciences, Technical Report No.7, ISSN 0158-9776, July.
11. IPCC (2001) *Climate Change 2001: The Scientific Basis*. Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, 944 pp., U.K.
12. IPCC (2007) *Climate Change 2007: The Physical Science Basis.* Summary for Policy Makers. Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).
13. Kamphuis, J.W (2000). *Introduction to Coastal Engineering and Management.* ISBN 981 02 3830 4, June.
14. Leuliette, E.W, Nerem, R.S and Mitchum, G, (2004). *"Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change"*, Mar. Geod.,27, 79-94.

15. Lord, D.B and Kulmar, M, (2000). *"The 1974 Storms Revisited: 25 Years Experience in Ocean Wave Measurement Along South East Australian Coast"*, Proceedings of the 27th International Conference on Coastal Engineering, Sydney, V1 pp 559-572, July.
16. Manly Hydraulics Laboratory (MHL, 1992). *Mid New South Wales Coastal Region, Tide-Storm Surge Analysis.* Technical Report No: MHL621.
17. Manly Hydraulics Laboratory (MHL, 1997). *New South Wales Coast May 1997 Storm Analysis.* Technical Report No: MHL886, December.
18. US National Aeronautical and Space administration Jet Propulsion Laboratory (NASA JPL, 2008). www.sealevel.jpl.nasa.gov
19. National Tidal Centre, Bureau of Meteorology (NTC, 2007). *Australian Baseline Sea Level Monitoring Project. Sea Level Data Summary Report: Jul06-Jun07".*
20. NSW Government (1990). *Coastline Management Manual.* ISBN 0 73057 506 3, September.
21. Patterson A.H, Blumberg, G.P, Couriel, E.D and Groskops, M (1997). *"Model and Prototype Behaviour of Effective Floating Breakwaters"*, Proceedings of the 13th Australasian Coastal and Ocean Engineering Conference, Christchurch, V2 pp 203-212, September.
22. PWD (1985). *"Elevated Ocean Levels Storms Affecting the NSW Coast 1880-1980"*, Report prepared for Coastal Engineering Branch, Public Works Department of NSW by Blain Bremner and Williams Pty Ltd in conjunction with Weatherex Meteorological Services Pty Ltd. Report No. 85041, December.
23. Ranasinghe R., R. McLoughlin, A. Short and G. Symonds (2004). *"The Southern Oscillation Index, Wave Climate, and Beach Rotation". Marine Geology*, Vol. 204, 273-287. (http://www.dlwc.nsw.gov.au/care/coast/marine_geology.html).
24. Ranasinghe R, P. Watson, D. Lord, D. Hanslow and P. Cowell (2007). *"Sea Level Rise, Coastal Recession and the Bruun Rule"*. Proceedings of the 18th Australasian Coastal and Ocean Engineering Conference, July.
25. University of Colorado at Boulder website (2008). www.sealevel.colorado.edu
26. USACE (2002). *Coastal Engineering Manual.* Engineer Manual 1110-2-1100, U.S Army Corps of Engineers, Washington, D.C (in 6 volumes).
27. Willoughby, M.A, (1991). *"Boat Waves and their Impact on the Shoreline and other Floating Craft"*, Report prepared by the MSB Waterways Authority, ref 91/01.
28. WP Geomarine (1998). *"Advice to Drummoyne Council"*, Report prepared by Willing and Partners (NSW) on behalf of Drummoyne Council, Report No. 3880.
29. You, Z.J (2007). *"Extrapolation of Extreme Wave height with a Proper Probability Distribution Function"*. Proceedings of the 18th Australasian Coastal and Ocean Engineering Conference, July.

11 GLOSSARY

Accretion	The accumulation of (beach) sediment, deposited by natural fluid flow processes.
Anomaly	The difference between an observed or measured value and one predicted by a model.
Anthropogenic	Resulting from human activity.
Astronomical Tide	The tidal levels and character which would result from gravitational effects, e.g. of the Earth, Sun and Moon, without any atmospheric or weather related influences.
Average Recurrence Interval (ARI)	The time interval that statistically would be expected to occur, on average, between events of a specific magnitude.
Backshore	(1). The upper part of the active beach above the normal reach of the tides (high water), but affected by large waves. (2). The accretion or erosion zone, located landward of ordinary high tide, which is normally wetted only by storm tides.
Barometric Pressure	The pressure from the weight of air in the atmosphere.
Barometric Setup	The increase in mean sea level caused by a fall in barometric pressure.
Bathymetry	The measurement of depths of water in oceans, seas and lakes; also the information derived from such measurements.
Beach Erosion	The offshore movement of beach materials from the sub-aerial beach by wave action, tidal currents, littoral currents or wind, predominantly during storms.
Beach Face	The section of the beach normally exposed to the action of wave uprush. The foreshore of the beach.
Beach Profile	A cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or sea wall, extend over the backshore, across the foreshore, and seaward underwater into the nearshore zone.
Beach	The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation. The seaward limit of a beach – unless otherwise specified – is the mean low water line.
Bed	The bottom of a watercourse, or any body of water.

Bench Mark	A mark affixed to a permanent object in tidal observations, or in a survey, to furnish a datum level.
Berm	On a beach: that area of shoreline lying between the swash zone and the dunal system.
Bore	A broken swell wave travelling shorewards across the surf zone.
Breaker Zone	The zone of coastal waters within which shoaling effects cause waves approaching the shoreline to break.
Breaking Waves	As waves increase in height through the shoaling process, the crest of the wave tends to speed up relative to the rest of the wave. Waves break when the speed of the crest exceeds the speed of advance of the wave as a whole. Waves can break in three modes: spilling, surging and plunging.
Breakwater	Offshore structure aligned parallel to the shore, sometimes shore-connected, that provides protection from waves.
Climate Change	Refers to any long term trend in mean sea level, wave height, wind speed, drift rate etc.
Coast	A strip of land of indefinite length and width (may be tens of kilometres) that extends from the seashore inland to the first major change in terrain features.
Coastal Currents	Those currents which flow roughly parallel to the shore and constitute a relatively uniform drift in the deeper water adjacent to the surf zone. These currents may be tidal currents, transient, wind-driven currents, or currents associated with the distribution of mass in local waters.
Coastal Defence	General term used to encompass both coastal protection against erosion and sea defence against flooding.
Coastal Processes	Collective term covering the action of natural forces on the shoreline, and the nearshore seabed.
Coastal Structures	Those structures on the coastline designed to protect and rebuild the coastline and/or enhance coastal amenity and use.
Coastal Zone	(1) General: The land-sea-air interface zone around continents and islands extending from the landward edge of a barrier beach or shoreline of coastal bay to the outer extent of the continental shelf. (2). Legislation: In NSW the “Coastal Zone” is a specific area which is described by definition in the Coastal Protection Act 1979.

Coastline	The line where terrestrial processes give way to marine processes, tidal currents, wind waves, etc.
Conservation	The protection of an area, or particular element within an area, accepting the dynamic nature of the environment and therefore allowing change.
Continental Shelf	The zone bordering a continent extending from the line of permanent immersion to the depth, usually about 100 m to 200 m, where there is a marked or rather steep descent toward the great depths.
Current	A current is a continuous, directed movement of water, generated by forces acting upon the water mass including tides, waves, winds and changes in salinity and temperature.
Datum	Any position or element in relation to which others are determined, as datum point, datum line, datum plane.
Design Still Water Level	The still water level used for design purposes – i.e. does not take into account wave setup and runup.
Design Wave Height	The wave height adopted for the purposes of designing coastal structures such as breakwaters and seawalls. It is chosen to ensure that the structures are not at undue risk of wave damage.
Design Wave	In the design of harbours, harbour works, etc., the type or types of waves selected as having the characteristics against which protection is desired.
Diffraction	The ‘spreading’ of waves into the lee of obstacles such as breakwaters by the transfer of wave energy along wave crests. Diffracted waves are lower in height than the incident waves.
East Australia Current	An ocean current that moves warm water in a counter clock-wise fashion down the east coast of Australia.
Ecosystem	The living organisms and the non-living environment interacting in a given area.
Elevation	The height of a point above a specified datum or reference point.

El Niño/La Niña	El Niño refers to the extensive warming of the central and eastern Pacific that leads to a major shift in weather patterns across the Pacific. In Australia (particularly eastern Australia), El Niño events are associated with an increased probability of drier conditions. The term La Niña refers to the extensive cooling of the central and eastern Pacific Ocean. In Australia (particularly eastern Australia), La Niña events are associated with increased probability of wetter conditions.
Embayment	(1) An indentation in a shoreline forming an open bay. (2) The formation of a bay.
Entrance	The entrance to a navigable bay, harbour or channel, inlet or mouth separating the ocean from an inland water body.
Erosion	Wearing away of the land by natural forces. On a beach, the carrying away of beach material by wave action, tidal currents or by deflation.
Estuary	(1) A semi-enclosed coastal body of water which has a free connection with the open sea. The seawater is usually measurably diluted with freshwater. (2) The part of the river that is affected by tides. (3) The zone or area of water in which freshwater and saltwater mingle and water is usually brackish due to daily mixing and layering of fresh and salt water.
Eustatic	A uniform global change in sea level that may reflect a change in the quantity of water in the ocean, or a change in the shape and capacity of the ocean basins.
Event	An occurrence meeting specified conditions, e.g. damage, a threshold wave height or a threshold water level.
Extreme Value Theory	A branch of statistics dealing with the extreme deviations from the median of probabaility distributions. The general theory sets out to assess the type of probability distributions generated by processes.
Fetch	The length of unobstructed open sea surface across which the wind can generate waves (generating area).
Foreshore	In general terms, the beach between mean higher high water and mean lower low water.
Gauge	An instrument that measures water level relative to a datum.

Global Positioning System (GPS)	A Global Navigation Satellite System (GNSS) developed by the United States Department of Defense that can be used to locate the position of a GPS receiver anywhere on earth.
Greenhouse Effect	A term used to describe the likely global warming predicted to accompany the increasing levels of carbon dioxide and other “greenhouse” gases in the atmosphere.
Greenhouse Gases	Gases in an atmosphere that absorb and emit radiation within the thermal infrared range.
High Water (HW)	Maximum height reached by a rising tide. The height may be solely due to the periodic tidal forces or it may have superimposed upon it the effects of prevailing meteorological conditions. Non-technically, also called the high tide.
Hydrography	The description and study of seas, lakes, rivers and other waters.
Intertidal	The zone between the high and low water marks.
Inverse Barometer Effect	The impact that atmospheric pressure has on sea level. Mean sea level (MSL) rises in areas of low atmospheric pressure and falls in areas of high pressure. Sea level rises by about 10 cm for every 10 hPa drop in atmospheric pressure.
Isostasy	Equilibrium in the earth's crust such that the forces tending to elevate landmasses balance the forces tending to depress landmasses.
La Niña	See *El Niño*
Littoral Currents	A current running parallel to the beach and generally caused by waves striking the shore at an angle.
Low Water (LW)	The minimum height reached by each falling tide. Non-technically, also called low tide.
Mean High Water (MHW)	The average elevation of all high waters recorded at a particular point or station over a considerable period of time, usually 19 years. For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 19-year value. All high water heights are included in the average where the type of tide is either semidiurnal or mixed.
Mean High Water Springs (MHWS)	The average height of the high water occurring at the time of spring tides.

Mean Low Water (MLW)	The average height of the low waters over a 19-year period. For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 19-year value.
Mean Low Water Springs (MLWS)	The average height of the low waters occurring at the time of the spring tides.
Mean Sea Level	The average height of the surface of the sea for all stages of the tide over a 19- year period, usually determined from hourly height readings.
Meteorology	Study of the atmosphere and its phenomena.
Nearshore	In beach terminology an indefinite zone extending seaward from the shoreline well beyond the breaker zone.
Ocean Current	A non-tidal current constituting a part of the general oceanic circulation. Ocean currents in the Australasian Region are significant in shaping marine environmental conditions and our climate and include: Antarctic Circumpolar Current, Leeuwin Current, Indonesian Throughflow and East Australian Current.
Oceanography	study of the physics, chemistry, biology and geology of the worlds oceans.
Offshore	In beach terminology, the comparatively flat zone of variable width, extending from the shoreface to the edge of the continental shelf. It is continually submerged.
Onshore Wind	A wind blowing landward from the sea.
Orthogonal	Perpendicular; at 90^{o} to; right angles to.
Orthophoto	An aerial photograph that has been geometrically corrected ("ortho-rectified") such that the scale of the photograph is uniform, meaning that the photo can be considered equivalent to a map.
Overtopping	Water carried over the top of a coastal defence due to wave run-up or surge action exceeding the crest height.
Physiographic	Describing or pertaining to the natural surface of the land.
Predicted Tide	The tide predicted by a computer program using tidal constants derived from measured data.
Probability Density Function	For a continuous function, the probability density function (pdf) is the probability that the variate has a specific value.
Profile (Beach)	See *Beach Profile.*

Recession	A net landward movement of the shoreline over a specified time.
Reflected Wave	That part of an incident wave that is returned (reflected) seaward when a wave impinges on a beach, seawall or other reflecting surface.
Reflection	The process by which the energy of the wave is returned seaward.
Refraction	The process by which the direction of a wave moving in shallow water at an angle to the bottom contours is changed. The part of the wave moving shoreward in shallower water travels more slowly than that portion in deeper water, causing the wave to turn or bend to become parallel to the contours.
Return Period	See *Average Recurrence Interval.*
Revetment	A facing of stone, concrete, etc., to protect an embankment, or shore structure, against erosion by wave action or currents. Refer also *Seawall.*
Runlines	Survey transects.
Run-up	The rush of water up a structure or beach on the breaking of a wave. The amount of run-up is the vertical height above stillwater level that the rush of water reaches.
Sand	An unconsolidated (geologically) mixture of inorganic soil (that may include disintegrated shells and coral) consisting of small but easily distinguishable grains ranging in size from about 0.062 mm to 2.0 mm.
Satellite Altimetry	Altimetry is a technique for measuring height. Satellite altimetry measures the time taken by a radar pulse to travel from the satellite antenna to the surface and back to the satellite receiver. Combined with precise satellite location data, altimetry measurements yield sea-surface heights.
Sea Defences	Works to prevent or alleviate flooding by the sea.
Sea Level Rise	The long term trend in movement of mean sea level.
Seawall	A structure separating land and water areas primarily to prevent erosion and other damage by wave action.
Sediment Budget	An accounting of the rate of sediment supply from all sources (credits) and the rate of sediment loss to all sinks (debits) from an area of coastline to obtain the net sediment supply/loss.

Sediment	Loose, fragments of rocks, minerals or organic material which are transported from their source for varying distances and deposited by air, wind, ice and water. Other sediments are precipitated from the overlying water or form chemically, in place. Sediment includes all the unconsolidated materials on the sea floor.
Semi-Diurnal Tides	Tides with a period, or time interval between two successive high or low waters, of about 12.5 hours. Tides along the New South Wales coast are semi-diurnal.
Shoaling	The influence of the seabed on wave behaviour. Such effects only become significant in water depths of 60m or less. Manifested as a reduction in wave speed, a shortening in wave length and an increase in wave height.
Shore	That strip of ground bordering any body of water which is alternately exposed or covered by tides and/or waves. A shore of unconsolidated material is usually called a beach.
Shoreface	The narrow zone seaward from the low tide shoreline permanently covered by water, over which the beach sands and gravels actively oscillate with changing wave conditions.
Shoreline	The intersection of a specified plane of water with the shore.
Significant Wave	A statistical term relating to the one-third highest waves of a given wave group and defined by the average of their heights and periods.
Significant Wave Height	The average height of the highest one third of waves recorded in a given monitoring period. Also referred to as $H_{1/3}$ or H_s.
Southern Oscillation Index (SOI)	An index (number) calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. Sustained negative values of the SOI often indicate El Niño episodes. Positive values of the SOI are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia, popularly known as a La Niña episode.
Spring Tide	A tide that occurs at or near the time of new or full moon, and which rises highest and falls lowest from the mean sea level (MSL).
Storm Surge	The increase in coastal water level caused by the effects of storms. Storm surge consists of two components: the increase in water level caused by the reduction in barometric pressure (barometric setup) and the increase in water level caused by the action of wind blowing over the sea surface (wind setup).

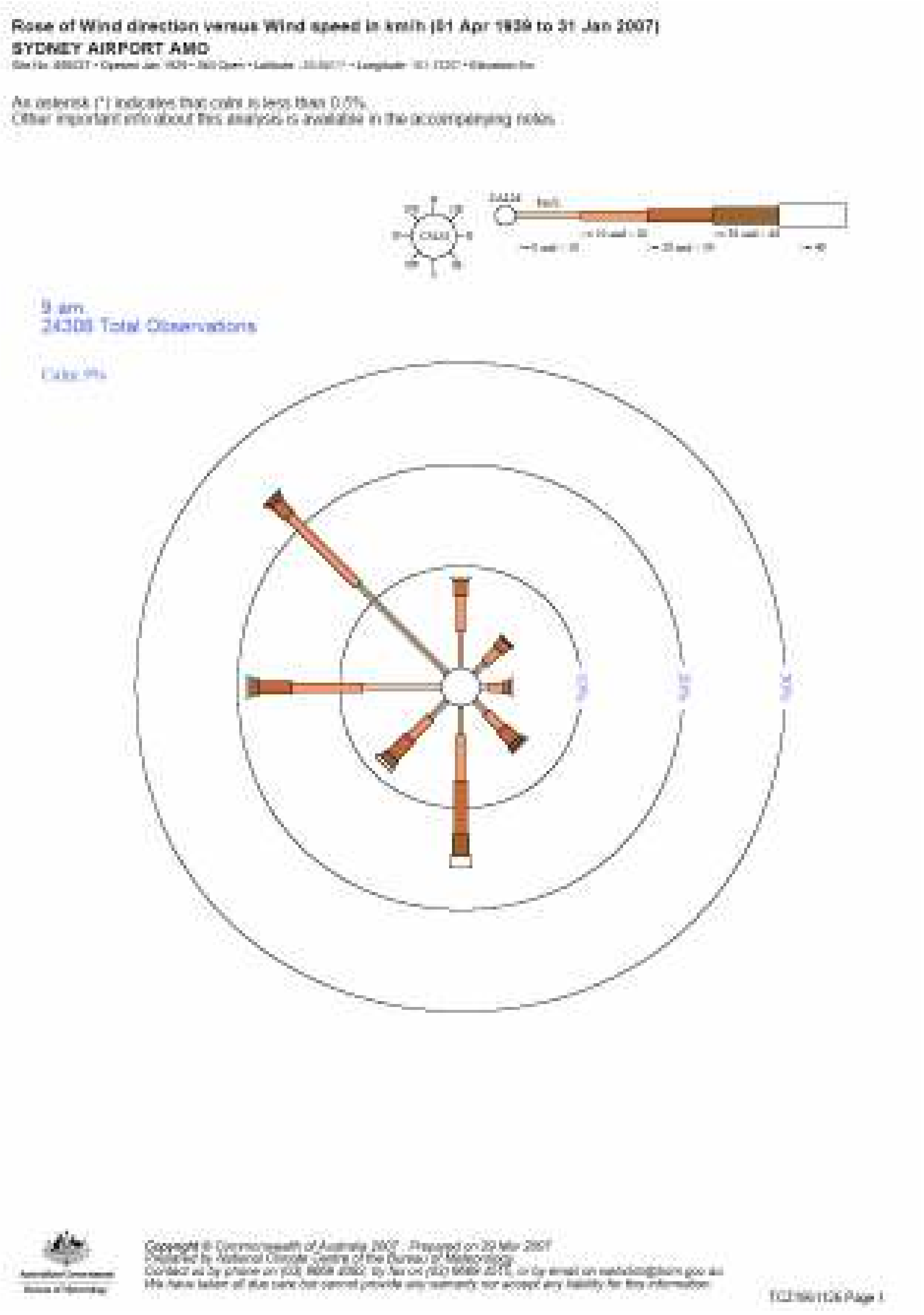
Surf Zone	Coastal waters between the breaker zone and the swash zone characterised by broken swell waves moving shorewards in the form of bores.
Survey (Hydrographical)	A survey that has as its principal purpose the determination of geometric and dynamic characteristics of bodies of water.
Swash Zone	That area of the shoreline characterised by wave uprush and retreat.
Swell Waves	Wind waves remote from the area of generation (fetch) having a uniform and orderly appearance characterised by regularly spaced wave crests.
Temporal	of or relating to or limited by time.
Tidal Constants	Tidal relations that remain practically constant for any location.
Tidal Wave	(1). A wave, in the oceans and seas, produced by tides and tidal currents. (2). Non-technical term in popular usage for an unusually high and destructive water level along a shore. It usually refers to storm surge or tsunami.
Tides	The regular rise and fall of sea level in response to the gravitational attraction of the sun, moon and planets. Tides along the New South Wales coastline are semi-diurnal in nature, i.e. they have a period of about 12.5 hours.
Tides (Spring)	A tide that occurs at or near the time of new or full moon, and which rises highest and falls lowest from the mean sea level (MSL) when the gravitational attraction of the sun and moon are in line. The spring tides occur about every 14 days, but, are highest during the Summer and Winter months.
Tides (King or Solstice)	In any one year there will be two spring tides which are the highest. These are referred to as “King” tides with one occurring during Summer and the other in Winter. The Summer “King” tide occurs when the gravitational attraction of the sun and moon are in line and the sun is closest to the earth (exhibiting its greatest gravitational influence). The Winter “King” tide occurs on the new moon when the sun is farthest from the earth, exhibiting its least gravitational influence.
Tsunami	Long period ocean waves generated by geological and tectonic disturbances below the sea. Incorrectly referred to as “tidal waves”, Tsunami travel at speeds of up to 800 km/hr in the open ocean, where they are of low height. However, tsunami can rise to a height of 10m or more through the shoaling process as they approach land.

Uprush	The rush of water up the foreshore following the breaking of a wave, also called swash or runup.
Water (Navigable)	The waters which are or can be used as water highways for commerce.
Wave	(1). An oscillatory movement in a body of water manifested by an alternate rise and fall of the surface. (2). A disturbance of the surface of a liquid body, as the ocean, in the form of a ridge, swell or hump.
Wave Climate	Average condition of the waves at a place, over a period of years, as shown by height, period, direction, etc.
Wave Energy	The average energy density per unit area of waves on the water surface and proportional to the wave height squared.
Wave Generation	Growth of wave energy by wind.
Wave Height	The vertical distance between a wave trough and a wave crest.
Wave Hindcasting	The estimation of wave climate from meteorological data (barometric pressure, wind) as opposed to wave measurement.
Wave Length	The distance between consecutive wave crests or wave troughs.
Wave Period	The time taken for consecutive wave crests or wave troughs to pass a given point.
Wave Regularity	The uniformity of the wave height, period and direction of the wave climate.
Wave Runup	The vertical distance above mean water level reached by the uprush of water from waves breaking across a beach or against a structure.
Wave Setup	The increase in water level within the surf zone above mean still water level caused by the breaking action of waves.
Wave Train	A series of waves originating from the same fetch with more or less the same wave characteristics.
Weathering	Decomposition of earth rocks, soils and their minerals through direct contact with the planet's atmosphere.
Wind Rose	A graphic tool used to give an overview of how wind speed and direction are typically distributed at a particular location.
Wind Setup	The increase in mean sea level caused by the ‘piling up’ of water on the coastline by the wind.

Wind Waves	The waves initially formed by the action of wind blowing over the sea surface. Wind waves are characterised by a range of heights, periods and wavelengths. As they leave the area of generation (fetch), wind waves develop a more ordered and uniform appearance and are referred to as swell or swell waves.

APPENDIX A

Bureau of Meteorology Wind Data for Sydney Airport AMO



Rose of Wind direction versus Wind speed in km/h (01 Apr 1939 to 31 Jan 2007)

SYDNEY AIRPORT AMO

An asterisk (*) indicates that calm is less than 0.5%.
Other important info about this analysis is available in the accompanying notes.

9 am
24308 Total Observations

Calm 9%

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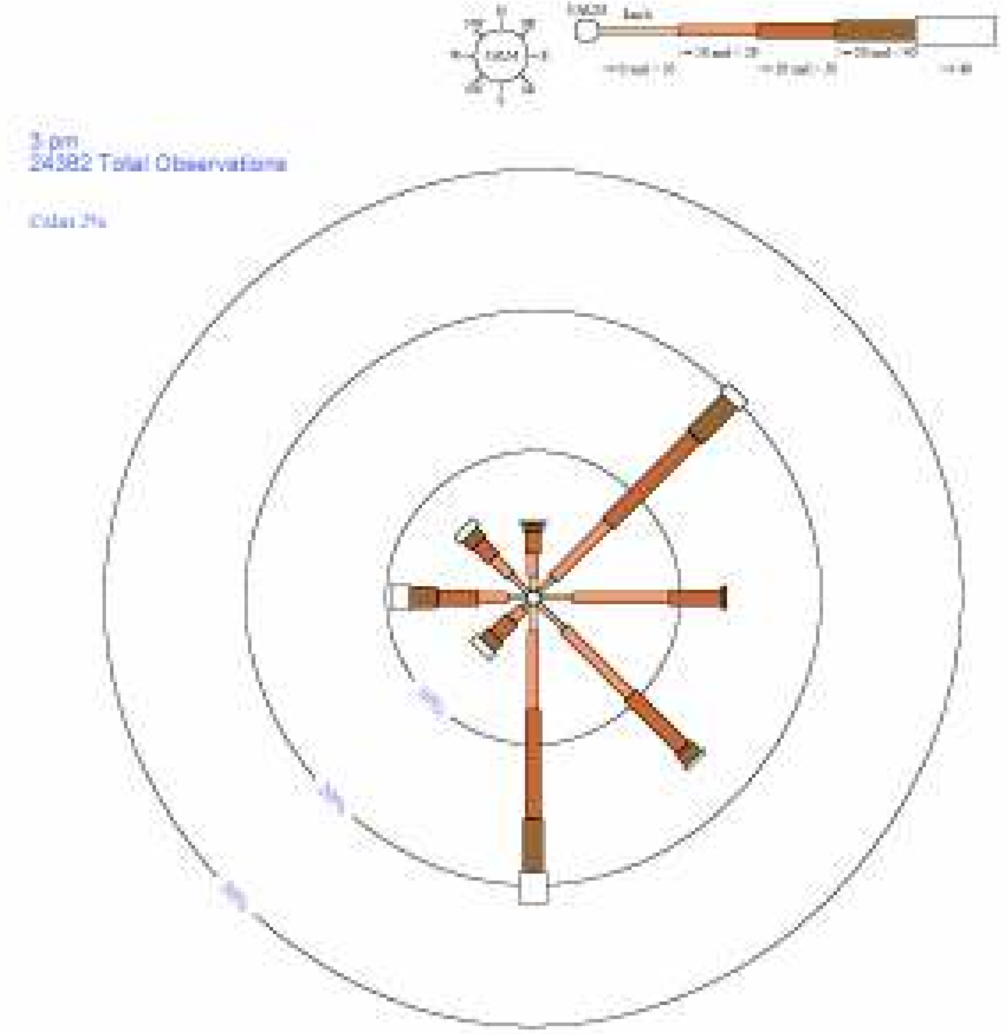
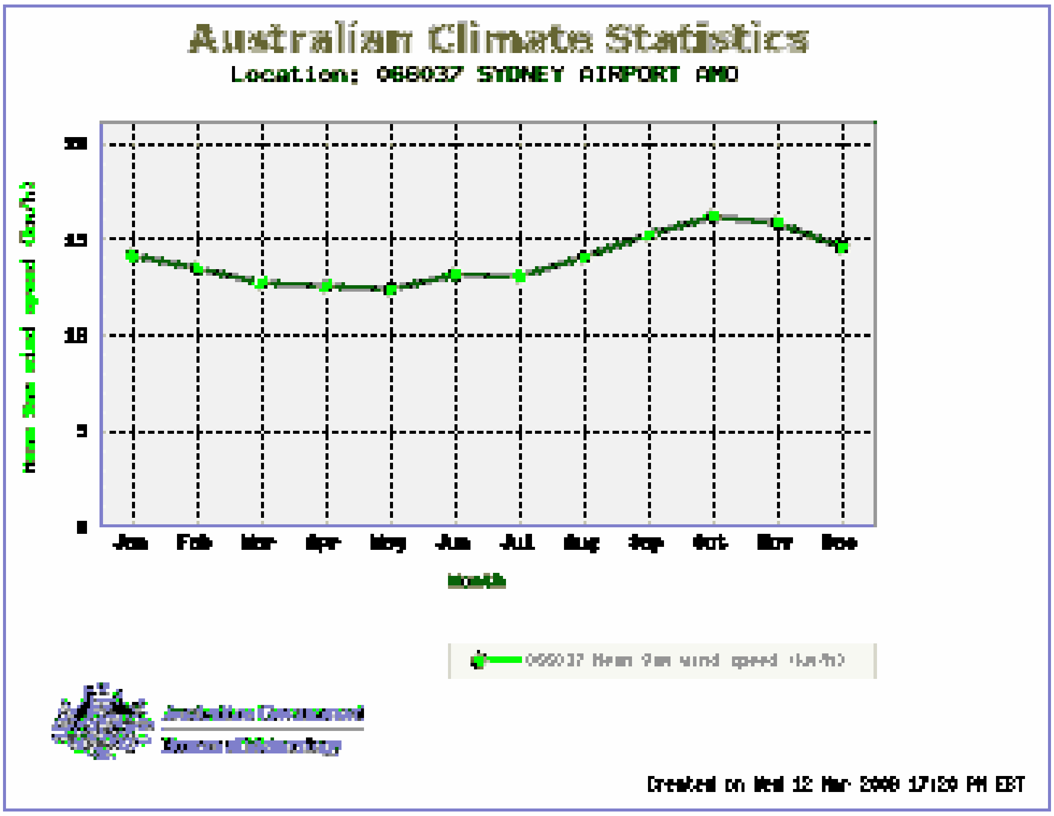
Prepared by National Climate Centre of the Bureau of Meteorology
We have taken all due care but cannot provide any warranty nor accept any liability for this information.

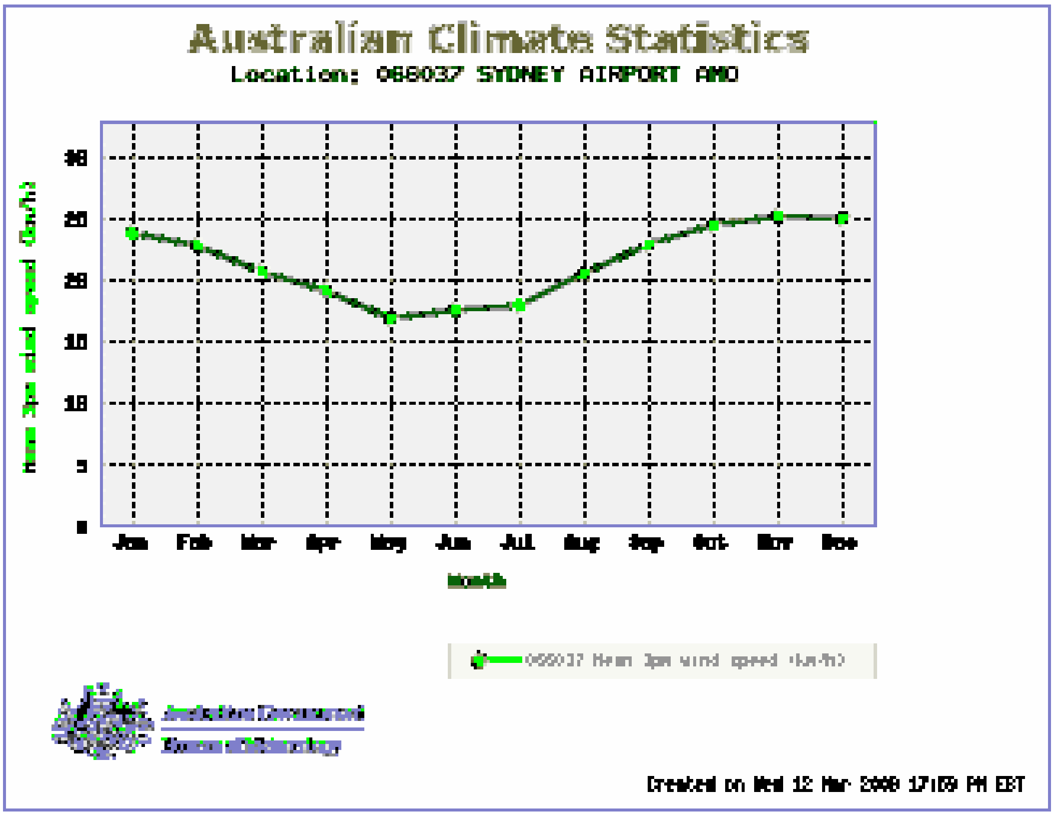
Rose of Wind direction versus Wind speed in km/h (01 Apr 1939 to 31 Jan 2007)

SYDNEY AIRPORT AMO

An asterisk (*) indicates that calm is less than 0.5%.
Other important info about this analysis is available in the accompanying notes.




Australian Climate Statistics
Location: 066037 SYDNEY AIRPORT AMO
Mean 9am wind speed (km/h)
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
066037 Mean 9am wind speed (km/h)
Australian Government
Bureau of Meteorology
Created on Wed 12 Mar 2008 17:20 PM EST


Australian Climate Statistics
Location: 066037 SYDNEY AIRPORT AMO
Mean 3pm wind speed (km/h)
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
066037 Mean 3pm wind speed (km/h)
Australian Government
Bureau of Meteorology
Created on Wed 12 Mar 2008 17:09 PM EST

APPENDIX B

Fort Denison Tide Level Analysis
(Manly Hydraulics Laboratory)

NSW DEPARTMENT OF COMMERCE, MANLY HYDRAULICS LABORATORY
110B KING STREET, MANLY VALE N.S.W. 2093, AUSTRALIA.
TELEPHONE 02-9949-0200

TIDAL LEVEL STATISTICS

STATION NAME:	Fort Denison
COMMENTS:	ACTUAL LEVELS
RECORDER TYPE:	N/A
LATITUDE/LONGITUDE:	33-51 DEG. SOUTH, 151-14 DEG. EAST
DATA START:	31-MAY-1914
DATA FINISH:	31-DEC-2006
TOTAL YEARS OF DATA:	92
DATABASE TIME INTERVAL (min):	60
DATUM:	LAT (approximates zero Camp Cove)
DATE OF ISSUE:	1501:12/12/2007
ANALYSIS PERFORMED BY:	PM using INTERACTIVE program WDBLCIX V1.0

Level (metres)	Normalised Frequency	No. Points in Class Interval	Cumulative Points	Return Period (Years)
2.4	1.26E-06	1	1	9.06E+01
2.35	1.26E-06	1	2	9.06E+01
2.32	1.26E-06	1	3	9.06E+01
2.3	5.04E-06	4	7	2.27E+01
2.27	3.78E-06	3	10	3.02E+01
2.26	2.52E-06	2	12	4.53E+01
2.25	1.26E-06	1	13	9.06E+01
2.24	1.26E-06	1	14	9.06E+01
2.23	3.78E-06	3	17	3.02E+01
2.22	5.04E-06	4	21	2.27E+01
2.21	2.52E-06	2	23	4.53E+01
2.2	2.64E-05	21	44	4.32E+00
2.19	1.89E-05	15	59	6.04E+00
2.18	1.26E-05	10	69	9.06E+00
2.17	1.26E-05	10	79	9.06E+00
2.16	1.51E-05	12	91	7.55E+00
2.15	1.76E-05	14	105	6.47E+00
2.14	4.15E-05	33	138	2.75E+00
2.13	2.39E-05	19	157	4.77E+00
2.12	2.14E-05	17	174	5.33E+00
2.11	3.65E-05	29	203	3.12E+00
2.1	1.17E-04	93	296	9.74E-01
2.09	4.15E-05	33	329	2.75E+00
2.08	9.69E-05	77	406	1.18E+00
2.07	6.67E-05	53	459	1.71E+00
2.06	7.05E-05	56	515	1.62E+00
2.05	1.31E-04	104	619	8.71E-01
2.04	8.31E-05	66	685	1.37E+00
2.03	6.67E-05	53	738	1.71E+00
2.02	1.96E-04	156	894	5.81E-01
2.01	1.71E-04	136	1030	6.66E-01
2	3.75E-04	298	1328	3.04E-01
1.99	2.54E-04	202	1530	4.49E-01
1.98	2.20E-04	175	1705	5.18E-01
1.97	1.42E-04	113	1818	8.02E-01
1.96	4.20E-04	334	2152	2.71E-01
1.95	2.91E-04	231	2383	3.92E-01
1.94	2.22E-04	176	2559	5.15E-01
1.93	4.68E-04	372	2931	2.44E-01

Continued from Previous Page

Level (metres)	Normalised Frequency	No. Points in Class Interval	Cumulative Points	Return Period (Years)
1.92	4.24E-04	337	3268	2.69E-01
1.91	2.62E-04	208	3476	4.36E-01
1.9	1.29E-03	1028	4504	8.82E-02
1.89	5.07E-04	403	4907	2.25E-01
1.88	3.56E-04	283	5190	3.20E-01
1.87	8.87E-04	705	5895	1.29E-01
1.86	6.53E-04	519	6414	1.75E-01
1.85	4.34E-04	345	6759	2.63E-01
1.84	1.20E-03	956	7715	9.48E-02
1.83	8.84E-04	702	8417	1.29E-01
1.82	5.19E-04	412	8829	2.20E-01
1.81	1.34E-03	1067	9896	8.49E-02
1.8	2.12E-03	1683	11579	5.38E-02
1.79	6.76E-04	537	12116	1.69E-01
1.78	1.85E-03	1470	13586	6.16E-02
1.77	1.23E-03	981	14567	9.24E-02
1.76	9.69E-04	770	15337	1.18E-01
1.75	2.02E-03	1603	16940	5.65E-02
1.74	1.54E-03	1220	18160	7.43E-02
1.73	1.04E-03	827	18987	1.10E-01
1.72	9.63E-04	765	19752	1.18E-01
1.71	3.19E-03	2537	22289	3.57E-02
1.7	3.09E-03	2458	24747	3.69E-02
1.69	1.36E-03	1078	25825	8.41E-02
1.68	3.50E-03	2783	28608	3.26E-02
1.67	1.27E-03	1011	29619	8.96E-02
1.66	1.52E-03	1204	30823	7.53E-02
1.65	4.26E-03	3386	34209	2.68E-02
1.64	1.47E-03	1167	35376	7.77E-02
1.63	1.49E-03	1185	36561	7.65E-02
1.62	5.18E-03	4113	40674	2.20E-02
1.61	1.70E-03	1351	42025	6.71E-02
1.6	4.87E-03	3870	45895	2.34E-02
1.59	4.92E-03	3906	49801	2.32E-02
1.58	3.21E-03	2553	52354	3.55E-02
1.57	1.75E-03	1388	53742	6.53E-02
1.56	5.14E-03	4085	57827	2.22E-02
1.55	3.27E-03	2598	60425	3.49E-02
1.54	2.25E-03	1787	62212	5.07E-02
1.53	5.99E-03	4755	66967	1.91E-02
1.52	3.44E-03	2731	69698	3.32E-02
1.51	2.65E-03	2108	71806	4.30E-02
1.5	1.02E-02	8121	79927	1.12E-02
1.49	3.69E-03	2930	82857	3.09E-02
1.48	2.92E-03	2322	85179	3.90E-02
1.47	7.30E-03	5801	90980	1.56E-02
1.46	4.96E-03	3937	94917	2.30E-02
1.45	2.91E-03	2308	97225	3.93E-02
1.44	7.55E-03	6000	103225	1.51E-02
1.43	4.44E-03	3526	106751	2.57E-02
1.42	2.97E-03	2359	109110	3.84E-02
1.41	8.85E-03	7028	116138	1.29E-02
1.4	9.80E-03	7786	123924	1.16E-02
1.39	3.28E-03	2607	126531	3.48E-02
1.38	8.00E-03	6354	132885	1.43E-02
1.37	5.65E-03	4489	137374	2.02E-02
1.36	3.81E-03	3023	140397	3.00E-02

Continued from Previous Page

Level (metres)	Normalised Frequency	No. Points in Class Interval	Cumulative Points	Return Period (Years)
1.35	9.57E-03	7603	148000	1.19E-02
1.34	5.61E-03	4453	152453	2.04E-02
1.33	3.52E-03	2796	155249	3.24E-02
1.32	8.52E-03	6766	162015	1.34E-02
1.31	6.23E-03	4946	166961	1.83E-02
1.3	1.05E-02	8312	175273	1.09E-02
1.29	1.01E-02	7991	183264	1.13E-02
1.28	6.17E-03	4903	188167	1.85E-02
1.27	3.69E-03	2930	191097	3.09E-02
1.26	1.02E-02	8070	199167	1.12E-02
1.25	5.60E-03	4445	203612	2.04E-02
1.24	3.86E-03	3070	206682	2.95E-02
1.23	1.14E-02	9026	215708	1.00E-02
1.22	6.03E-03	4790	220498	1.89E-02
1.21	3.95E-03	3137	223635	2.89E-02
1.2	1.57E-02	12437	236072	7.29E-03
1.19	6.28E-03	4990	241062	1.82E-02
1.18	4.02E-03	3193	244255	2.84E-02
1.17	1.07E-02	8488	252743	1.07E-02
1.16	7.82E-03	6215	258958	1.46E-02
1.15	3.98E-03	3165	262123	2.86E-02
1.14	9.59E-03	7619	269742	1.19E-02
1.13	6.17E-03	4898	274640	1.85E-02
1.12	4.27E-03	3394	278034	2.67E-02
1.11	1.11E-02	8838	286872	1.03E-02
1.1	1.19E-02	9470	296342	9.57E-03
1.09	4.36E-03	3463	299805	2.62E-02
1.08	3.72E-03	2953	302758	3.07E-02
1.07	1.15E-02	9120	311878	9.94E-03
1.06	4.42E-03	3509	315387	2.58E-02
1.05	4.50E-03	3575	318962	2.53E-02
1.04	1.26E-02	9979	328941	9.08E-03
1.03	3.63E-03	2880	331821	3.15E-02
1.02	3.66E-03	2906	334727	3.12E-02
1.01	1.25E-02	9950	344677	9.11E-03
1	9.47E-03	7521	352198	1.20E-02
0.99	3.67E-03	2919	355117	3.10E-02
0.98	1.34E-02	10606	365723	8.54E-03
0.97	3.34E-03	2650	368373	3.42E-02
0.96	4.29E-03	3411	371784	2.66E-02
0.95	9.24E-03	7341	379125	1.23E-02
0.94	5.51E-03	4379	383504	2.07E-02
0.93	3.40E-03	2703	386207	3.35E-02
0.92	1.01E-02	8004	394211	1.13E-02
0.91	6.14E-03	4881	399092	1.86E-02
0.9	9.33E-03	7411	406503	1.22E-02
0.89	9.26E-03	7356	413859	1.23E-02
0.88	4.89E-03	3885	417744	2.33E-02
0.87	3.98E-03	3164	420908	2.86E-02
0.86	1.11E-02	8787	429695	1.03E-02
0.85	6.38E-03	5071	434766	1.79E-02
0.84	4.31E-03	3426	438192	2.65E-02
0.83	8.88E-03	7057	445249	1.28E-02
0.82	5.62E-03	4467	449716	2.03E-02
0.81	3.68E-03	2926	452642	3.10E-02
0.8	1.69E-02	13413	466055	6.76E-03
0.79	5.57E-03	4427	470482	2.05E-02

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Level (metres)	Normalised Frequency	No. Points in Class Interval	Cumulative Points	Return Period (Years)
0.78	3.83E-03	3041	473523	2.98E-02
0.77	1.00E-02	7970	481493	1.14E-02
0.76	6.78E-03	5384	486877	1.68E-02
0.75	4.09E-03	3251	490128	2.79E-02
0.74	1.08E-02	8543	498671	1.06E-02
0.73	6.57E-03	5221	503892	1.74E-02
0.72	4.04E-03	3209	507101	2.82E-02
0.71	9.65E-03	7664	514765	1.18E-02
0.7	1.42E-02	11254	526019	8.05E-03
0.69	4.64E-03	3688	529707	2.46E-02
0.68	1.15E-02	9115	538822	9.94E-03
0.67	6.91E-03	5489	544311	1.65E-02
0.66	5.19E-03	4119	548430	2.20E-02
0.65	1.04E-02	8240	556670	1.10E-02
0.64	6.46E-03	5134	561804	1.77E-02
0.63	4.14E-03	3285	565089	2.76E-02
0.62	1.26E-02	10043	575132	9.02E-03
0.61	7.06E-03	5605	580737	1.62E-02
0.6	1.16E-02	9194	589931	9.86E-03
0.59	1.12E-02	8911	598842	1.02E-02
0.58	6.73E-03	5344	604186	1.70E-02
0.57	3.89E-03	3094	607280	2.93E-02
0.56	1.27E-02	10063	617343	9.01E-03
0.55	8.24E-03	6548	623891	1.38E-02
0.54	4.30E-03	3416	627307	2.65E-02
0.53	1.05E-02	8306	635613	1.09E-02
0.52	7.09E-03	5635	641248	1.61E-02
0.51	3.94E-03	3131	644379	2.89E-02
0.5	1.77E-02	14043	658422	6.45E-03
0.49	5.81E-03	4613	663035	1.96E-02
0.48	4.65E-03	3694	666729	2.45E-02
0.47	1.00E-02	7967	674696	1.14E-02
0.46	6.85E-03	5442	680138	1.67E-02
0.45	4.25E-03	3380	683518	2.68E-02
0.44	3.61E-03	2870	686388	3.16E-02
0.43	1.22E-02	9688	696076	9.35E-03
0.42	3.34E-03	2652	698728	3.42E-02
0.41	3.73E-03	2966	701694	3.06E-02
0.4	1.53E-02	12170	713864	7.45E-03
0.39	3.16E-03	2509	716373	3.61E-02
0.38	2.91E-03	2315	718688	3.91E-02
0.37	1.14E-02	9093	727781	9.97E-03
0.36	3.12E-03	2476	730257	3.66E-02
0.35	2.75E-03	2187	732444	4.14E-02
0.34	8.98E-03	7135	739579	1.27E-02
0.33	2.39E-03	1895	741474	4.78E-02
0.32	2.20E-03	1744	743218	5.20E-02
0.31	7.21E-03	5728	748946	1.58E-02
0.3	6.27E-03	4983	753929	1.82E-02
0.29	1.92E-03	1525	755454	5.94E-02
0.28	5.59E-03	4442	759896	2.04E-02
0.27	2.77E-03	2198	762094	4.12E-02
0.26	1.74E-03	1380	763474	6.57E-02
0.25	5.38E-03	4272	767746	2.12E-02
0.24	2.35E-03	1866	769612	4.86E-02
0.23	1.53E-03	1216	770828	7.45E-02
0.22	4.06E-03	3222	774050	2.81E-02

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Level (metres)	**Normalised Frequency**	**No. Points in Class Interval**	**Cumulative Points**	**Return Period (Years)**
0.21	1.76E-03	1399	775449	6.48E-02
0.2	2.65E-03	2104	777553	4.31E-02
0.19	3.51E-03	2792	780345	3.25E-02
0.18	1.26E-03	1002	781347	9.04E-02
0.17	7.64E-04	607	781954	1.49E-01
0.16	2.70E-03	2141	784095	4.23E-02
0.15	1.04E-03	823	784918	1.10E-01
0.14	6.11E-04	485	785403	1.87E-01
0.13	2.04E-03	1622	787025	5.59E-02
0.12	8.40E-04	667	787692	1.36E-01
0.11	4.15E-04	330	788022	2.75E-01
0.1	1.89E-03	1501	789523	6.04E-02
0.09	7.25E-04	576	790099	1.57E-01
0.08	2.93E-04	233	790332	3.89E-01
0.07	1.08E-03	860	791192	1.05E-01
0.06	4.85E-04	385	791577	2.35E-01
0.05	2.35E-04	187	791764	4.85E-01
0.04	7.53E-04	598	792362	1.52E-01
0.03	2.76E-04	219	792581	4.14E-01
0.02	1.59E-04	126	792707	7.19E-01
0.01	5.88E-04	467	793174	1.94E-01
0	2.44E-04	194	793368	4.67E-01
-0.01	1.10E-04	87	793455	1.04E+00
-0.02	3.51E-04	279	793734	3.25E-01
-0.03	1.04E-04	83	793817	1.09E+00
-0.04	5.79E-05	46	793863	1.97E+00
-0.05	2.49E-04	198	794061	4.58E-01
-0.06	8.18E-05	65	794126	1.39E+00
-0.07	2.52E-05	20	794146	4.53E+00
-0.08	1.26E-04	100	794246	9.06E-01
-0.09	3.90E-05	31	794277	2.92E+00
-0.1	2.64E-05	21	794298	4.32E+00
-0.11	6.04E-05	48	794346	1.89E+00
-0.12	1.38E-05	11	794357	8.24E+00
-0.13	6.29E-06	5	794362	1.81E+01
-0.14	2.77E-05	22	794384	4.12E+00
-0.15	1.26E-06	1	794385	9.06E+01
-0.16	2.52E-06	2	794387	4.53E+01
-0.17	1.38E-05	11	794398	8.24E+00
-0.18	1.26E-06	1	794399	9.06E+01
-0.19	1.26E-06	1	794400	9.06E+01

APPENDIX C

Sydney Harbour Design Still Water Level Analysis (Gumbel Probability Distribution)

C1. Introduction

Extreme water level heights are essential parameters to be defined when considering the vulnerability of Fort Denison to the existing physical coastal processes and future sea level rise scenarios. The continuous record of reliable ocean water levels from the Fort Denison tide gauge facility since 1914, provides an exceptional data record for Sydney Harbour from which one can extrapolate extreme design water parameters using an assigned probability distribution function (You, 2007).

Continuous hourly water level recordings are available from the Fort Denison tide gauge data for the period from 31 May 1914 to present. Manly Hydraulics Laboratory have analysed the 794,400 available hourly data points to provide a summary of the normalised distribution of measured water levels for each cm graduation in height (refer Appendix B).

C2. Extreme Value Analysis

There are a broad range of probability distribution functions available for application in estimating extreme values. For many coastal design parameters, for example ocean wave heights, there may only be a maximum of 20 to 30 years of quality recorded data. The application of extreme value theory is therefore required to extrapolate design values with a recurrence interval significantly longer than that of the data record.

Each probability distribution function deals with the extreme ends of the data spectrum (or tail) in slightly different ways depending on the underlying mathematical relationship used (least squares, exponential, lognormal, etc). The substantial data set available for ocean water levels at Fort Denison enables various probability functions to be fitted to the data and examined for the closeness of the fit in representing the majority of data points.

An FT-I (or Gumbel) probability distribution function has been applied to the Fort Denison data supplied by Manly Hydraulics Laboratory (Appendix B). When fitting trendlines to data, the square of the correlation co-efficient (R^2) provides an indication of how a trendline accounts for the variation in a data field. In the case of the current analysis of the Fort Denison water level data, the determined Gumbel variate (X) exhibits an R^2 of 0.9997, indicating that 99.97% of the variation in the data is accounted for by the fitted linear trendline, an almost perfect mathematical representation of the measured data (refer Figure C1).

Using the Gumbel variate, we can readily generate a design chart to estimate the Average Recurrence Interval (ARI) of ocean water levels of relevance at Fort Denison (refer Figure C2). Relevant design levels have been summarised in Table 5.7.

C3. References

You, Z.J (2007). *"Extrapolation of Extreme Wave height with a Proper Probability Distribution Function"*. Proceedings of the 18th Australasian Coastal and Ocean Engineering Conference, July.

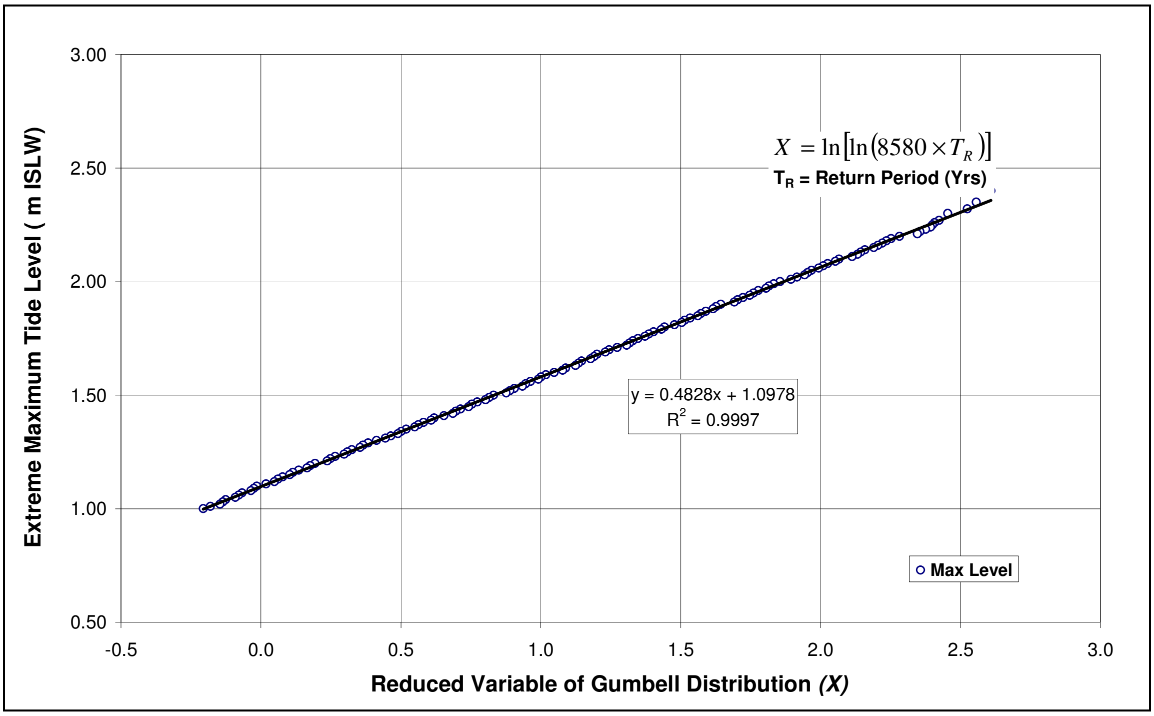


Figure C1: Gumbel Variate for Fort Denison Water Level Data

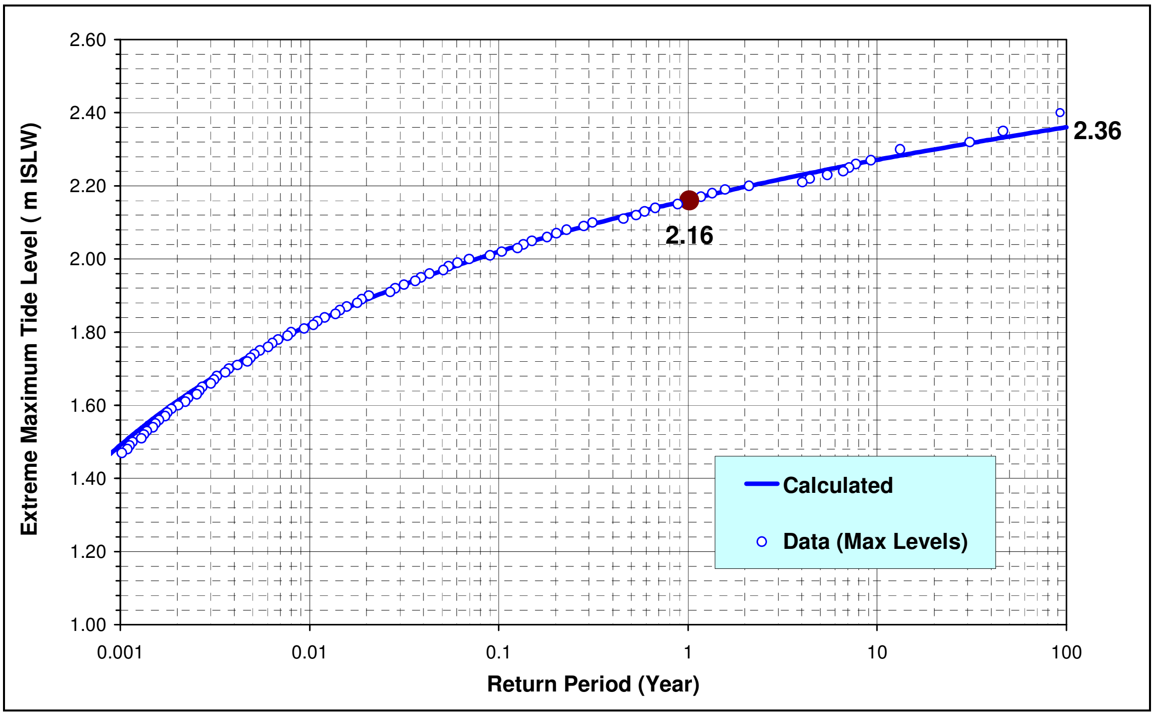


Figure C2: Design Still Water Levels for Fort Denison

APPENDIX D

Design Wave Field for Fort Denison

D1. Introduction

Fort Denison is situated some 6km from the ocean entrance at South Head and is not exposed to long period, high energy swell wave activity. The majority of swell wave energy directed into the harbour is dissipated on the shorelines around Middle Head. Swells modified by refraction and diffraction processes have been observed to penetrate into the harbour as far as Nielsen Park and Rose Bay.

Although Fort Denison is not subjected to ocean swell waves, the site is exposed to local wind driven seas comprising comparatively low energy and short period waves which can be superimposed on wave fields generated from the multitude of recreational and commercial vessels using the heavily trafficked working harbour.

Wave energy is a function of both the wave height and wave period (the time between successive wave crests). As such, the extent of wave energy dissipated around natural harbour foreshores or against fixed structures and revetments will vary depending on the derivation of the wave source. Within most harbour or estuary confines, wind generated waves are limited to heights of 0.2 to 0.5m and periods ranging from 2 to 4 seconds, depending on available wind fetch lengths and the strength of prevailing winds (Edwards & Lord, 1995). Boat generated waves within speed restricted navigable harbours and estuaries of NSW are generally limited, though the wave periods generated by different types of vessels have been measured in the range more commonly associated with high energy deep ocean swell (8 to 10 seconds).

With changing wind patterns and so many vessel movements that produce characteristically different boat wave signatures, wave fields approaching Fort Denison are highly variable, random and exceedingly complex, consisting of a range of heights and speeds generated from multiple sources and directions. For design purposes, it would be preferable to have long-term wave data records from within the harbour that automatically record the totality of the wave field. This however, is rarely the case and indeed no such record exists for the waters in the vicinity of Fort Denison for design purposes. Under these circumstances, it is valuable to separate out the relevant contributions from locally generated seas and that of boat generated waves in order to look at their respective impacts. With knowledge of individual wind and boat wave climates an “equivalent” or representative wave field for design purposes can be developed that considers the likelihood of both wind driven seas and boat generated wave fields occurring simultaneously.

D2. Design Local Wind Generated Wave Climate

Surrounded by water, Fort Denison is subjected to local wind generated seas from all directions. Using wave hindcasting techniques and wind data, it is possible to estimate the magnitude of waves that can be generated in each direction based on the length of water over which the waves are able to form or build.

The length of the water body, the depth of the water and the wind speed and duration are all governing factors affecting wind wave growth over time. Wind waves generated over infinitely large fetches (such as oceans) will generally be limited by the duration of the wind and are termed “duration limited” waves. Conversely, within smaller bodies of water such as harbours and bays, wind wave generation is most likely to be limited by the length of water over which the waves can build, and the corresponding wave field generated is thus deemed to be “fetch limited”.

The Coastal Engineering Manual (USACE, 2002) advises equations governing wave growth with fetch are:

$$\frac{gH_{m0}}{u_*^2} = 4.13x10^{-2}\left(\frac{gX}{u_*^2}\right)^{0.5}$$ [Equation 1]

and

$$\frac{gT_p}{u_*^2} = 0.751\left(\frac{gX}{u_*^2}\right)^{\frac{1}{3}}$$ [Equation 2]

$$C_D = \frac{u_*^2}{U_{10}^2}$$

$$C_D = 0.001\left(1.1 + 0.035xU_{10}\right)$$

Where: X = straight line fetch distance over which the wind blows (m);

H_{m0} = energy-based significant wave height (m);

C_D = drag co-efficient;

U_{10} = wind speed at 10m elevation above mean sea level (m/sec);

u_* = friction velocity (m/sec).

Table D1 summarises the design wind wave climate at Fort Denison.

Table D1: Local Wind Driven Seas – Maximum Wave Height, Period and Power

Dir.	Max Wind Speed (1)		Design Wind Speed U_{10} (m/s) (2)	Fetch (m) (3)	F* (4)	F^*_{eff} (5)	Fetch Limit. (Y/N) (6)	H_{mo} (m) (7)	Period (s) (7)	Power (W/m) (8)
	km/h	m/s								
N	70	19.4	17.9	1130	34.5	153.2	Y	0.33	1.5	166
NE	70	19.4	19.9	1330	32.9	130.8	Y	0.41	1.7	276
E	80	22.2	22.8	2950	55.8	107.1	Y	0.71	2.3	1160
SE	100	27.8	28.5	1190	14.4	76.6	Y	0.59	1.9	654
S	110	30.6	31.3	1000	10.0	66.4	Y	0.61	1.9	683
SW	90	25.0	23.1	910	16.8	105.1	Y	0.40	1.6	250
W	90	25.0	23.1	1650	30.5	105.1	Y	0.54	1.9	553
NW	80	22.2	20.5	780	18.2	125.4	Y	0.32	1.4	146

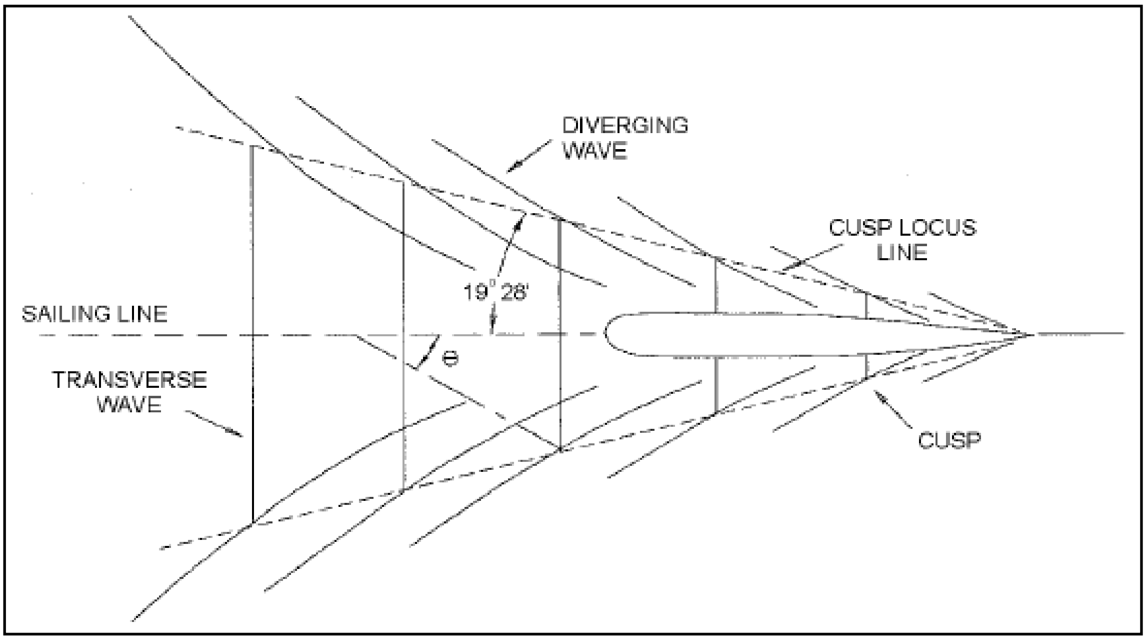
Notes:
1. Values are maximum average 10 minute wind speeds from Sydney Airport AMO (refer Table 5.1).
2. Design Wind Speed has been corrected to account for a range of factors including standard height used in wave hindcasting (10m), equivalent wind speed over water and to equate maximum wind speed with standard hourly average wind speed (USACE, 2002).
3. The fetch distance for irregular shorelines such as Sydney Harbour are calculated as the distance to shore averaged over 12° either side of the wind direction using radials at 3° intervals.
4. Dimensionless fetch length.
5. Effective fetch length for limited storm duration.
6. If $F^* < F^*_{eff}$ then waves are fetch limited and Equations 1 and 2 above apply.
7. Peak Period and H_{mo} determined from Equations 1 and 2 above (USACE, 2002).
8. Wave power calculated through a vertical plane in the direction of wave advance (USACE, 2002).

D3. Design Boat Wave Conditions

As a vessel travels across the water surface, a variable pressure distribution develops along the vessels hull. As it is propelled through the water, pressure increases at the bow (front) and stern (rear) and drops along the midsection. These pressure gradients in turn, generate a set of waves that propagate out from the vessel bow (diverging waves) and another generally lower set of waves (transverse waves) that propagate out from the vessel stern (USACE, 2002). The diverging waves are larger and steeper than the transverse waves. Also, the transverse waves from the bow and stern generally combine into a single series of waves while the two diverging wave trains remain separated (Willoughby, 1991).The pattern of wave crests generated at the bow of a vessel moving at constant speed in deepwater is indicated in Figure D1.

The heights of the resulting waves depend on a range of factors including the speed of the vessel, the shape of the hull, and the distance from the sailing line, though the period and direction of the resulting wave train only depend on the vessel speed and the water depth (USACE, 2002).

Figure D1: Wave Pattern Generated at a Vessel Bow (USACE, 2002).



Once fully formed, the group of waves emanating from a vessel is termed a “wave train”. In deepwater, the height of the waves attenuates with distance, although the wave period will generally remain unchanged (Glamore et al, 2007). The degree of attenuation (or loss in wave height) for the diverging wave train has been measured to be inversely proportional to the cube of the distance from the sailing line. Edwards and Lord (1995) summarised boat wave measurements from a range of investigations conducted within Sydney Harbour (refer Table D2).

Table D2: Measured Boat Waves in Sydney Harbour (Edwards and Lord, 1998)

Location	Craft Class	Averages		Maxima		Distance From Sail Line (m)	Power (W/m) (5)
		H_{max} (m)	T (sec)	H_{max} (m)	T (sec)		
Sydney Cove (1)	Hydrofoil	0.45	2.3	0.72	2.0	50-100	1017
	Lady Ferry	0.25	2.2	0.44	2.2		418
	Water Taxi	0.38	2.2	0.44	1.8		342
Manly Cove (1)	Hydrofoil	0.56	2.4	0.87	2.6	50-100	1931
Drummoyne (2)	River Cat	0.32	8.4	0.40	10.0	100-200	1570
	First Fleet Ferry	0.45	4.0	0.54	4.3		1230
	Cruiser	0.2	2.6	0.25	3.0		184
Pulpit Point(3)	River Cat	0.45	4.0	0.60	5.2	25-150	1837
	First Fleet Ferry	0.2	2.3	0.25	2.5		153
Sydney Harbour (4)	25m Cat Ferry			0.62	2.0	90	754
	Lady Ferry			0.39	2.8		418

Notes:
1. (Cox and Blumberg, 1984).
2. (WPGeomarine, 1998).
3. (Patterson, et al, 1997). This study made the observation that due to instrument problems the wave height measurements were generally inconsistent with the observed conditions.
4. (Blumberg, 1991).
5. After Edwards and Lord (1998). Wave power calculated through a vertical plane in the direction of wave advance (UASACE, 2002) based on maxima values for wave height and period.

D4. Equivalent Design Wave Field

When considering wave parameters for the design of structures and overtopping heights within the Sydney Harbour environment, it is relevant that the design wave field is likely to be a combination of boat generated waves superimposed over the top of wind generated seas. Whilst the wind generated seas may persist on timescales that could exceed several hours, boat waves are generated by moving vessels which produce a very different wave signature which will generally only impact upon a given water surface for as little as several minutes.

If long-term local wave data records existed in the vicinity of Fort Denison, the data could be readily transformed into a design wave climate that inherently incorporates the co-existence of boat and wind waves. In the absence of such records, some consideration needs to be given in a design context to the fact that both sets of waves co-exist with separate contributions of energy and power. The separate components can be co-incident at the shoreline amplifying the impacts of the individual wave constituents (boat and wind generated waves).

The are very few guidelines available for combining the relevant contributions from the separate wave climates, however, some practical engineering judgement has been applied to determine a representative or “equivalent” wave climate for design purposes to accommodate the contribution of each of the respective wave fields (wind and boat). In this context, it is highly improbable that either commercial or recreational boating vessels would be operating in conditions coincident with the maximum measured wind speeds recorded for each of the respective cardinal wind directions.

For the current investigation, a representative or “equivalent” design wave climate has been based upon the maximum boat wave power (refer Table D2) generated because this limiting condition is substantially higher than the power output generated by any of the hindcast wind wave fields. A nominal proportion (50%) of the maximum wind wave power has been added to estimate the maximum power likely to be generated by the coincidence of both wave climates. By considering the originating boat and wind wave periods, the combined wave power can be converted to an “equivalent” design wave height. The “equivalent” design wave parameters advised in Table D3 have been used in the form of a sensitivity analysis to determine maximum wave runup levels.

It is recognised that the published literature available on measured boat wave heights in Sydney Harbour is relatively limited. For this reason, the largest documented boat wave heights from Edwards and Lord (1998) have been considered as the limiting case. This is likely to be conservative due to the fact that boat waves decay in height proportional to the distance away from the sailing line of the vessel and the calculation technique applied inherently assumes that the maximum conditions will be applicable adjacent to the structure and directed with maximum impact (at 90°).

In the absence of long-term site specific measured wave climate data, the concept of the representative or “equivalent” design wave condition presented in this report is considered reasonable and sufficiently conservative to be used as an upper bound condition for estimating wave forces and runup levels of relevance for Fort Denison.

Table D3: Equivalent Design Wave Conditions for Fort Denison

Feature	Wind Waves		Boat Wave Max Power (W/m) (2)	Total Power (W/m) (1) + (2)	Equivalent Design Wave Condition			
	Dir.	Max Power (W/m) (1)			Condition 1 (3)		Condition 2 (4)	
					H_{mo} (m)	Period (s)	H_{mo} (m)	Period (s)
Western Seawall	W	196	1931	2127	1.06	1.9	0.91	2.6
	NW	73	1931	2004	1.19	1.4	0.89	2.6
	N	59	1931	1990	1.14	1.5	0.88	2.6
Tide Room	N	59	1931	1990	1.14	1.5	0.88	2.6
	NE	138	1931	2069	1.11	1.7	0.90	2.6
	E	410	1931	2341	1.02	2.3	0.96	2.6
Eastern Seawall	E	410	1931	2341	1.01	2.3	0.96	2.6
	SE	327	1931	2258	1.10	1.9	0.94	2.6
	S	242	1931	2173	1.09	1.9	0.92	2.6
Slipyard/BBQ Area	S	242	1931	2173	1.09	1.9	0.92	2.6
	SW	125	1931	2056	1.15	1.6	0.90	2.6
	W	196	1931	2127	1.06	1.9	0.91	2.6

Notes:
1. The maximum wind wave power is the proportion of power directed at 90 degrees to the structure and then reduced by 50% to account for likelihood of coincidence with maximum boat wave climate.
2. The maximum boat wave power obtained from Table D2.
3. Equivalent Design wave condition “1” is based on the underlying wind wave period.
4. Equivalent Design wave condition “2” is based on the underlying boat wave period.

D5. References

Blumberg, G.P, (1991). *Pers Comms*, Referenced in Willoughby (1991).

Cox, R.J and Blumberg, G.P, (1984). *"Opera House Covered Walkway – Marine Hydraulic Studies"*, University of NSW Water Research Laboratory, Technical Report No. 84/16.

Edwards, S and Lord, D.B (1998). *"Boat Waves and their Effect on the Shoreline of NSW Harbours and Inlets"*, Proceedings of the 8th Annual NSW Coastal Conference, Batemans Bay, 10-13 November.

Glamore, W.C and Badenhop, A, (2007). *"Managing and Assessing Boat Wake Waves"*, Proceedings of the 18th Australasian Coastal and Ocean Engineering Conference, Melbourne, July.

Glamore, W (2008). *"A Decision Support Tool for Assessing the Impact of Boat Wake Waves on Inland Waterways"*, On-Course, PIANC, pp 5-18, October.

Kamphuis, J.W (2000). *Introduction to Coastal Engineering and Management.* ISBN 981 02 3830 4, June.

Patterson A.H, Blumberg, G.P, Couriel, E.D and Groskops, M (1997). *"Model and prototype Behaviour of Effective Floating Breakwaters"*, Proceedings of the 13th Australasian Coastal and Ocean Engineering Conference, Christchurch, V2 pp 203-212, September.

USACE (2002). *Coastal Engineering Manual.* Engineer Manual 1110-2-1100, U.S Army Corps of Engineers, Washington, D.C (in 6 volumes).

Willoughby, M.A, (1991). *"Boat Waves and their Impact on the Shoreline and other Floating Craft"*, Report prepared by the MSB Waterways Authority, ref 91/01.

WP Geomarine (1998). *"Advice to Drummoyne Council"*, Report prepared by Willing and Partners (NSW) on behalf of Drummoyne Council, Report No. 3880.

APPENDIX E

Design Wave Runup Assessment

E1. Introduction

The actual runup from waves is relatively dynamic and highly variable. It is usually expressed as a height measured vertically above the still water level (R_u), exceeded by a small percentage of waves. Various approaches are available for determining the $R_{u2\%}$ which relates to the runup height exceeded by 2% of incident waves and is commonly used for design purposes.

Although the wave climate on Sydney Harbour in the vicinity of Fort Denison due to wind and boat waves climates is significantly less than that experienced on the open coast from swell, runup from wave energy dissipation against the external stone walls of the Fort is not insignificant. Near vertical, blockwork structures, may be liable to intense local wave impact pressures, may overtop suddenly or severely, reflecting much of the incident wave energy (EurOtop, 2007).

The height of runup from waves dissipating energy against an impermeable vertical stone wall depends on several factors including wave height and period, profile of the nearshore area, depth of water and wave regularity. The water depth in particular at the toe of the structure relative to the size of the wave can dramatically alter the capacity of the wave to break at the structure.

Fort Denison has been constructed with near vertical, external stone walls founded on the original rock promontory. This rock platform forms an apron around the Fort extending out from the toe of the wall at heights generally varying within ± 0.5m AHD. The extent of the rock apron is clearly visible in Figures E1 and E2.

The rock apron around the Fort generally extends seaward across a shelf with a width up to 10m, but is less prominent on the north-western side. Beyond the visible periphery of the rock apron, the bathymetry steepens markedly. Depending on wave characteristics and water levels, the presence of such a feature can significantly influence wave breaking behaviour, runup and overtopping.

In general if the Still Water Level (SWL) is within 1.4 times the significant wave height above the seaward edge of the apron or berm feature, the incoming wave will be moderated and the associated wave runup potential will be reduced compared to a foreshore where there are no such attributes. Alternatively, if the height of the SWL above the seaward edge of the berm feature is greater than 1.4 times the incoming significant wave height, the wave runup potential is not considered to be affected or moderated by the rock apron. Thus in order to provide reasonable estimates of design runup levels and overtopping rates, it is imperative to have accurate wave, water level and survey data, particularly relating to toe and crest levels of walls and the surrounding bathymetry.

E2. Design Runup Calculations

The Coastal Engineering Manual (USACE, 2002) advises that runup on impermeable slopes for irregular waves can be described by Equation 1 (see over page).

$$\frac{R_{ui\%}}{H_s} = \left(A\xi + C\right)\gamma_r \gamma_b \gamma_h \gamma_\beta \qquad \text{[Equation 1]}$$

Where: $R_{ui\%}$ = runup level exceeded by *i* percent of the incident waves measured above the SWL (m);
H_s = significant wave height (m);
$A,\ C$ = co-efficients dependant on ξ and *i* but related to the reference case of a smooth, straight impermeable slope;
ξ = surf-similarity parameter, ξ_{om} or ξ_{op} ;
γ_r = reduction factor for surface roughness (γ_r = 1 for smooth slopes);
γ_b = reduction factor for influence of a berm (γ_b = 1 for non-bermed profiles);
γ_h = reduction factor for influence of shallow water conditions (γ_h = 1 for Rayleigh distributed waves);
γ_β = factor for influence of angle of incidence β of the waves (γ_β = 1 for head-on long crested waves, ie., β = 0°);

The mean relationship, taken as the reference case for Equation 1 is represented by the following expression:

$$\frac{R_{u2\%}}{H_s} = \begin{array}{cc} 1.5\xi_{op} & for\ 0.5 < \xi_{op} \leq 2 \\ 3.0 & for\, 2 < \xi_{op} < 3-4 \end{array} \qquad \text{[Equation 2]}$$

However, the Technical Advisory Committee on Water Defence in Holland, advise the incorporation of a small safety factor for use in design purposes, which can be represented by the following expression:

$$\frac{R_{u2\%}}{H_s} = \begin{array}{cc} 1.6\xi_{op} & for\ 0.5 < \xi_{op} \leq 2 \\ 3.2 & for\, 2 < \xi_{op} < 3-4 \end{array} \qquad \text{[Equation 3]}$$

Using Equation 3, $R_{u2\%}$ design runup levels have been calculated at locations A, B, C and D (refer Figure E3) for the equivalent design wave climate (refer Appendix D), superimposed on a broad range of design ARI water levels and for various planning horizons (2050 and 2100) incorporating provision for Low, Medium and High sea level rise scenarios. Tables E1a to E4c summarise the limiting (or maximum) design runup level relevant to each location around Fort Denison.

E3. References

EurOtop (2007). *“Wave Overtopping of Sea Defences and Related Structures: Assessment Manual”*, Produced by Environmental Agency (UK), Coastal Engineering Research Council (Germany) and Rijkswaterstaat (Netherlands), August.

USACE (2002). *Coastal Engineering Manual.* Engineer Manual 1110-2-1100, U.S Army Corps of Engineers, Washington, D.C (in 6 volumes).

Figure E1: Rock berm apron at base of eastern seawall exposed at low tide.

Figure E2: Rock berm apron at base of south-western seawall exposed at low tide.

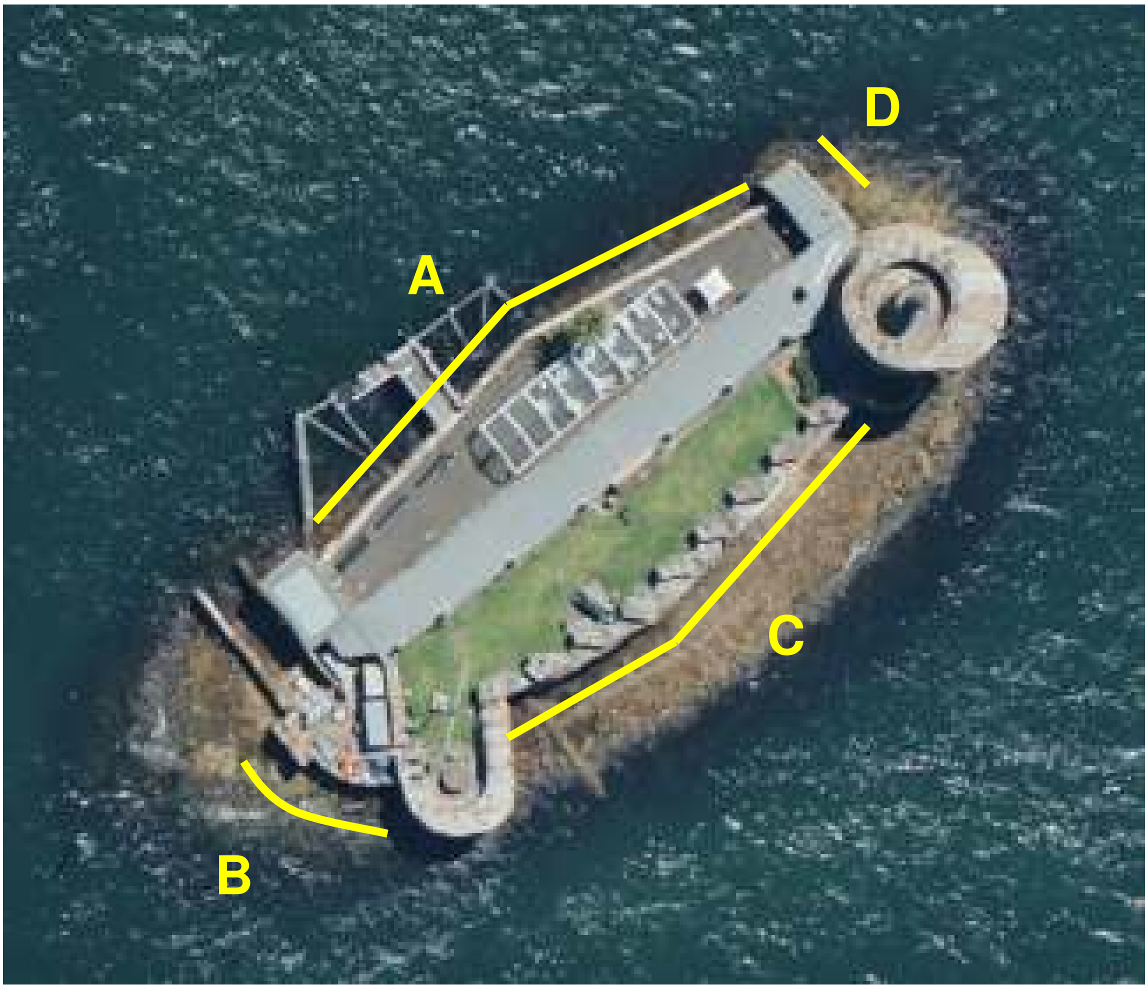


Figure E3: Location of design wave runup calculations.

Table E1a: 2008 Design Wave Runup Levels (Location A, Western Seawall)

2% WAVE RUNUP LEVELS (2008)													
Wave Details			**Structure**			**Water Level**			**Runup Details**				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.19	1.4	0 (NW)	-0.79	2.67	80	0.02	NA	0.965	9.1	3.81	4.773	2.103	
						0.05		1.045			4.853	2.183	
						0.1		1.095			4.903	2.233	
						1		1.235			5.043	2.373	
						2		1.275			5.083	2.413	
						5		1.315			5.123	2.453	
						10		1.345			5.153	2.483	
						20		1.375			5.183	2.513	
						50		1.415			5.223	2.553	
						100		1.435			5.243	2.573	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels for respective ARIs derived from Table 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.5m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock "berm" is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

Table E1b: 2050 Design Wave Runup Levels (Location A, Western Seawall)

2% WAVE RUNUP LEVELS (2050)													
Wave Details			**Structure**			**Water Level**			**Runup Details**				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.19	1.4	0 (NW)	-0.79	2.67	80	0.02	L	1.005	9.1	3.81	4.813	2.143	
							M	1.175			4.983	2.313	
							H	1.345			5.153	2.483	
						0.05	L	1.085			4.893	2.223	
							M	1.255			5.063	2.393	
							H	1.425			5.233	2.563	
						0.1	L	1.135			4.943	2.273	
							M	1.305			5.113	2.443	
							H	1.475			5.283	2.613	
						1	L	1.275			5.083	2.413	
							M	1.445			5.253	2.583	
							H	1.615			5.423	2.753	
						2	L	1.315			5.123	2.453	
							M	1.485			5.293	2.623	
							H	1.655			5.463	2.793	
						5	L	1.355			5.163	2.493	
							M	1.525			5.333	2.663	
							H	1.695			5.503	2.833	
						10	L	1.385			5.193	2.523	
							M	1.555			5.363	2.693	
							H	1.725			5.533	2.863	
						20	L	1.415			5.223	2.553	
							M	1.585			5.393	2.723	
							H	1.755			5.563	2.893	
						50	L	1.455			5.263	2.593	
							M	1.625			5.433	2.763	
							H	1.795			5.603	2.933	
						100	L	1.475			5.283	2.613	
							M	1.645			5.453	2.783	
							H	1.815			5.623	2.953	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.5m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock “berm” is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

Table E1c: 2100 Design Wave Runup Levels (Location A, Western Seawall)

2% WAVE RUNUP LEVELS (2100)													
Wave Details			**Structure**			**Water Level**			**Runup Details**				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.19	1.4	0 (NW)	-0.79	2.67	80	0.02	L	1.125	9.1	3.81	4.933	2.263	
							M	1.495			5.303	2.633	
							H	1.855			5.663	2.993	
						0.05	L	1.205			5.013	2.343	
							M	1.575			5.383	2.713	
							H	1.935			5.743	3.073	
						0.1	L	1.255			5.063	2.393	
							M	1.625			5.433	2.763	
							H	1.985			5.793	3.123	
						1	L	1.395			5.203	2.533	
							M	1.765			5.573	2.903	
							H	2.125			5.933	3.263	
						2	L	1.435			5.243	2.573	
							M	1.805			5.613	2.943	
							H	2.165			5.973	3.303	
						5	L	1.475			5.283	2.613	
							M	1.845			5.653	2.983	
							H	2.205			6.013	3.343	
						10	L	1.505			5.313	2.643	
							M	1.875			5.683	3.013	
							H	2.235			6.043	3.373	
						20	L	1.535			5.343	2.673	
							M	1.905			5.713	3.043	
							H	2.265			6.073	3.403	
						50	L	1.575			5.383	2.713	
							M	1.945			5.753	3.083	
							H	2.305			6.113	3.443	
						100	L	1.595			5.403	2.733	
							M	1.965			5.773	3.103	
							H	2.325			6.133	3.463	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.5m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock “berm” is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

Table E2a: 2008 Design Wave Runup Levels (Location B, Slipyard/BBQ Area)

2% WAVE RUNUP LEVELS (2008)														
Wave Details			**Structure**			**Water Level**			**Runup Details**					
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.15	1.6	0 (SW)	0.15	2.84	80	0.02	NA	0.965	10.6	3.68	4.65	1.81	
						0.05		1.045			4.73	1.89	
						0.1		1.095			4.78	1.94	
						1		1.235			4.92	2.08	
						2		1.275			4.96	2.12	
						5		1.315			5.00	2.16	
						10		1.345			5.03	2.19	
						20		1.375			5.06	2.22	
						50		1.415			5.10	2.26	
						100		1.435			5.12	2.28	

Notes:
1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels for respective ARIs derived from Table 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. The seaward edge of the surrounding rock apron (approx -0.8m AHD) is not located within 1.41 times the H_s of the design SWLs considered and therefore the calculated $R_{u2\%}$ would not be expected to be moderated by any berm effect of the apron.

Table E2b: 2050 Design Wave Runup Levels (Location B, Slipyard/BBQ Area)

2% WAVE RUNUP LEVELS (2050)													
Wave Details			**Structure**			**Water Level**			**Runup Details**				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.15	1.6	0 (SW)	0.15	2.84	80	0.02	L	1.005	10.6	3.68	4.685	1.845	
							M	1.175			4.855	2.015	
							H	1.345			5.025	2.185	
						0.05	L	1.085			4.765	1.925	
							M	1.255			4.935	2.095	
							H	1.425			5.105	2.265	
						0.1	L	1.135			4.815	1.975	
							M	1.305			4.985	2.145	
							H	1.475			5.155	2.315	
						1	L	1.275			4.955	2.115	
							M	1.445			5.125	2.285	
							H	1.615			5.295	2.455	
						2	L	1.315			4.995	2.155	
							M	1.485			5.165	2.325	
							H	1.655			5.335	2.495	
						5	L	1.355			5.035	2.195	
							M	1.525			5.205	2.365	
							H	1.695			5.375	2.535	
						10	L	1.385			5.065	2.225	
							M	1.555			5.235	2.395	
							H	1.725			5.405	2.565	
						20	L	1.415			5.095	2.255	
							M	1.585			5.265	2.425	
							H	1.755			5.435	2.595	
						50	L	1.455			5.135	2.295	
							M	1.625			5.305	2.465	
							H	1.795			5.475	2.635	
						100	L	1.475			5.155	2.315	
							M	1.645			5.325	2.485	
							H	1.815			5.495	2.655	

Notes:
1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].

Table E2c: 2100 Design Wave Runup Levels (Location B, Slipyard/BBQ Area)

2% WAVE RUNUP LEVELS (2100)													
Wave Details			Structure			Water Level			Runup Details				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.15	1.6	0 (SW)	0.15	2.84	80	0.02	L	1.125	10.6	3.68	4.805	1.965	
							M	1.495			5.175	2.335	
							H	1.855			5.535	2.695	
						0.05	L	1.205			4.885	2.045	
							M	1.575			5.255	2.415	
							H	1.935			5.615	2.775	
						0.1	L	1.255			4.935	2.095	
							M	1.625			5.305	2.465	
							H	1.985			5.665	2.825	
						1	L	1.395			5.075	2.235	
							M	1.765			5.445	2.605	
							H	2.125			5.805	2.965	
						2	L	1.435			5.115	2.275	
							M	1.805			5.485	2.645	
							H	2.165			5.845	3.005	
						5	L	1.475			5.155	2.315	
							M	1.845			5.525	2.685	
							H	2.205			5.885	3.045	
						10	L	1.505			5.185	2.345	
							M	1.875			5.555	2.715	
							H	2.235			5.915	3.075	
						20	L	1.535			5.215	2.375	
							M	1.905			5.585	2.745	
							H	2.265			5.945	3.105	
						50	L	1.575			5.255	2.415	
							M	1.945			5.625	2.785	
							H	2.305			5.985	3.145	
						100	L	1.595			5.275	2.435	
							M	1.965			5.645	2.805	
							H	2.325			6.005	3.165	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected "High", Medium" or "Low" sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].

Table E3a: 2008 Design Wave Runup Levels (Location C, Eastern Seawall)

2% WAVE RUNUP LEVELS (2008)														
Wave Details			**Structure**			**Water Level**			**Runup Details**					
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.10	1.9	0 (SE)	-0.29	5.57	80	0.02	NA	0.965	12.8	3.52	4.485		1.085
						0.05		1.045			4.565		1.005
						0.1		1.095			4.615		0.955
						1		1.235			4.755		0.815
						2		1.275			4.795		0.775
						5		1.315			4.835		0.735
						10		1.345			4.865		0.705
						20		1.375			4.895		0.675
						50		1.415			4.935		0.635
						100		1.435			4.955		0.615

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels for respective ARIs derived from Table 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.5m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock "berm" is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

Table E3b: 2050 Design Wave Runup Levels (Location C, Eastern Seawall)

2% WAVE RUNUP LEVELS (2050)

Wave Details			Structure			Water Level			Runup Details				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.10	1.9	0 (SE)	-0.43	5.56	80	0.02	L	1.005	12.8	3.52	4.525		1.045
							M	1.175			4.695		0.875
							H	1.345			4.865		0.705
						0.05	L	1.085			4.605		0.965
							M	1.255			4.775		0.795
							H	1.425			4.945		0.625
						0.1	L	1.135			4.655		0.915
							M	1.305			4.825		0.745
							H	1.475			4.995		0.575
						1	L	1.275			4.795		0.775
							M	1.445			4.965		0.605
							H	1.615			5.135		0.435
						2	L	1.315			4.835		0.735
							M	1.485			5.005		0.565
							H	1.655			5.175		0.395
						5	L	1.355			4.875		0.695
							M	1.525			5.045		0.525
							H	1.695			5.215		0.355
						10	L	1.385			4.905		0.665
							M	1.555			5.075		0.495
							H	1.725			5.245		0.325
						20	L	1.415			4.935		0.635
							M	1.585			5.105		0.465
							H	1.755			5.275		0.295
						50	L	1.455			4.975		0.595
							M	1.625			5.145		0.425
							H	1.795			5.315		0.255
						100	L	1.475			4.995		0.575
							M	1.645			5.165		0.405
							H	1.815			5.335		0.235

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.5m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock “berm” is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

Table E3c: 2100 Design Wave Runup Levels (Location C, Eastern Seawall)

2% WAVE RUNUP LEVELS (2100)

Wave Details			Structure			Water Level			Runup Details				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Crest of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above wall (m)	Freeboard (m)
1.10	1.9	0 (SE)	-0.43	5.56	80	0.02	L	1.125	12.8	3.52	4.645		0.925
							M	1.495			5.015		0.555
							H	1.855			5.375		0.195
						0.05	L	1.205			4.725		0.845
							M	1.575			5.095		0.475
							H	1.935			5.455		0.115
						0.1	L	1.255			4.775		0.795
							M	1.625			5.145		0.425
							H	1.985			5.505		0.065
						1	L	1.395			4.915		0.655
							M	1.765			5.285		0.285
							H	2.125			5.645	0.075	
						2	L	1.435			4.955		0.615
							M	1.805			5.325		0.245
							H	2.165			5.685	0.115	
						5	L	1.475			4.995		0.575
							M	1.845			5.365		0.205
							H	2.205			5.725	0.155	
						10	L	1.505			5.025		0.545
							M	1.875			5.395		0.175
							H	2.235			5.755	0.185	
						20	L	1.535			5.055		0.515
							M	1.905			5.425		0.145
							H	2.265			5.785	0.215	
						50	L	1.575			5.095		0.475
							M	1.945			5.465		0.105
							H	2.305			5.825	0.255	
						100	L	1.595			5.115		0.455
							M	1.965			5.485		0.085
							H	2.325			5.845	0.275	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].

Table E4a: 2050 Design Wave Runup Levels (Location D, Tide Room)

2% WAVE RUNUP LEVELS (2008)													
Wave Details			**Structure**			**Water Level**			**Runup Details**				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Roof of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above roof (m)	Freeboard (m)
1.14	1.5	0 (NE)	-0.12	4.85	80	0.02	NA	0.965	10.0	3.65	4.613		0.237
						0.05		1.045			4.693		0.157
						0.1		1.095			4.743		0.107
						1		1.235			4.883	0.033	
						2		1.275			4.923	0.073	
						5		1.315			4.963	0.113	
						10		1.345			4.993	0.143	
						20		1.375			5.023	0.173	
						50		1.415			5.063	0.213	
						100		1.435			5.083	0.233	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels for respective ARIs derived from Table 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.2m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock "berm" is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

Table E4b: 2050 Design Wave Runup Levels (Location D, Tide Room)

2% WAVE RUNUP LEVELS (2050)

Wave Details			Structure			Water Level			Runup Details				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Roof of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above roof (m)	Freeboard (m)
1.14	1.5	0 (NE)	-0.12	4.85	80	0.02	L	1.005	12.8	3.52	4.653		0.197
							M	1.175			4.823		0.027
							H	1.345			4.993	0.143	
						0.05	L	1.085			4.733		0.117
							M	1.255			4.903	0.053	
							H	1.425			5.073	0.223	
						0.1	L	1.135			4.783		0.067
							M	1.305			4.953	0.103	
							H	1.475			5.123	0.273	
						1	L	1.275			4.923	0.073	
							M	1.445			5.093	0.243	
							H	1.615			5.263	0.413	
						2	L	1.315			4.963	0.113	
							M	1.485			5.133	0.283	
							H	1.655			5.303	0.453	
						5	L	1.355			5.003	0.153	
							M	1.525			5.173	0.323	
							H	1.695			5.343	0.493	
						10	L	1.385			5.033	0.183	
							M	1.555			5.203	0.353	
							H	1.725			5.373	0.523	
						20	L	1.415			5.063	0.213	
							M	1.585			5.233	0.383	
							H	1.755			5.403	0.553	
						50	L	1.455			5.103	0.253	
							M	1.625			5.273	0.423	
							H	1.795			5.443	0.593	
						100	L	1.475			5.123	0.273	
							M	1.645			5.293	0.443	
							H	1.815			5.463	0.613	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected "High", Medium" or "Low" sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.2m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock "berm" is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

Table E4c: 2100 Design Wave Runup Levels (Location D, Tide Room)

2% WAVE RUNUP LEVELS (2100)													
Wave Details			**Structure**			**Water Level**			**Runup Details**				
Significant Wave Height (H_s) (m)	Significant Wave Period (T_s) (s)	Angle of Approach (β) (deg)	RL Toe of Structure (m AHD)	RL Roof of Structure (m AHD)	Wall Slope (α) (Degrees)	Average Recurrence Interval	Sea level Rise Scenario (L, M, H)	Design Still Water Level (m AHD)	Surf Similarity Parameter (ξ_{op})	Runup above SWL ($R_{u2\%}$)	2% Design Wave Runup Level (m AHD)	Runup height above roof (m)	Freeboard (m)
1.14	1.5	0 (NE)	-0.12	4.85	80	0.02	L	1.125	12.8	3.52	4.773		0.077
							M	1.495			5.143	0.293	
							H	1.855			5.503	0.653	
						0.05	L	1.205			4.853	0.003	
							M	1.575			5.223	0.373	
							H	1.935			5.583	0.733	
						0.1	L	1.255			4.903	0.053	
							M	1.625			5.273	0.423	
							H	1.985			5.633	0.783	
						1	L	1.395			5.043	0.193	
							M	1.765			5.413	0.563	
							H	2.125			5.773	0.923	
						2	L	1.435			5.083	0.233	
							M	1.805			5.453	0.603	
							H	2.165			5.813	0.963	
						5	L	1.475			5.123	0.273	
							M	1.845			5.493	0.643	
							H	2.205			5.853	1.003	
						10	L	1.505			5.153	0.303	
							M	1.875			5.523	0.673	
							H	2.235			5.883	1.033	
						20	L	1.535			5.183	0.333	
							M	1.905			5.553	0.703	
							H	2.265			5.913	1.063	
						50	L	1.575			5.223	0.373	
							M	1.945			5.593	0.743	
							H	2.305			5.953	1.103	
						100	L	1.595			5.243	0.393	
							M	1.965			5.613	0.763	
							H	2.325			5.973	1.123	

Notes:

1. Wave details relate to the equivalent design wave parameters derived from Table D3 (Appendix D). Only the limiting condition (highest runup producing wave field) has been indicated.
2. Design still water levels including those incorporating projected “High”, Medium” or “Low” sea level rise projections derived from Tables 5.2 and 5.3.
3. All relevant levels based on Australian Height Datum (AHD).
4. Reduction factors (γ_r, γ_b, γ_h, γ_β) have all been set to 1.
5. The toe RL is the lowest position around the base of the structure along the rock apron. The lower the toe, the less likely the rock apron will influence the equivalent wave climate.
6. Pale Blue Numbers indicate the freeboard between the 2% wave runup level and the height of the wall structure measured in metres. [Runup is contained by the structure].
7. Red Numbers indicate the height of the 2% wave runup level above the minimum height of the wall structure measured in metres. [Runup exceeds the structure].
8. Grey levels indicate that that the seaward edge of the surrounding rock apron (approx -0.2m AHD) is within 1.41 times the H_s of the design SWL and that the calculated $R_{u2\%}$ would be expected to be moderated by the berm effect of the apron. In general, the extent of influence of the rock “berm” is negligible for the more extreme design water levels and has therefore not been included in the calculation of design runup levels.

APPENDIX F

Photos around Fort Denison taken on 26 November 2007 coinciding with measured 1.95m ISLW peak tide event

(Photos courtesy Cath Snelgrove and Rebecca Wise, DECC)

Figure F1: Slipway and West Room at SW end of Fort at 0915 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F2: Western Seawall at 0915 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F3: Tide Room and Western Seawall at NE end of Fort at 0915 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F4: Martello Tower and Tide Room at NE end of Fort at 0915 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F5: Slipway and West Room at SW end of Fort at 0845 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F6: Slipway at SW end of Fort at 0845 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F7: Jetty at NW side of Fort at 0915 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F8: Slipway at NW side of Fort at 0915 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F9: Ferry wave against slipway at SW end of Fort at 0900 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F10: Ferry wave overtopping slipway at SW end of Fort at 0900 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

Figure F11: Ocean ingress beneath sub-flooring of function room in the Barracks at 0945 hrs. Measured water level is 1.90m ISLW (0.975m AHD).

Figure F12: Ocean ingress beneath sub-flooring of function room in the Barracks at 0945 hrs. Measured water level is 1.90m ISLW (0.975m AHD).

Figure F13: Martello Tower at NE end of Fort at 0915 hrs. Measured water level is 1.95m ISLW (1.025m AHD).

APPENDIX G

Photos around Fort Denison Delineating Survey Levels of Relevant Features

(Photos courtesy Phil Watson, DECC)

Figure G1: Northern portion of Western Seawall and Tide Room at 1100 hrs on 6 November 2007. Measured water level is 0.53m ISLW (-0.395m AHD).

Figure G2: Western Seawall at 1100 hrs on 6 November 2007. Measured water level is 0.53m ISLW (-0.395m AHD).

Figure G3: Boat landing area and entry to Western Terrace forecourt.

Figure G4: Western Terrace asphalted forecourt area used for dining/functions.

Figure G5: NW corner of Western Terrace forecourt.

Figure G6: SW corner of Western Terrace forecourt.

Figure G7: Eastern Seawall and Martello Tower exposed at 1145 hrs (low tide) on 6 November 2007. Measured water level is 0.48m ISLW (-0.445m AHD).

Figure F8: Grassed Eastern Terrace and Eastern Seawall.

Figure G9: Slipyard and BBQ area.