Sydney Harbour Sea Level Rise Vulnerability Studies

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ABSTRACT: The NSW Department of Environment, Climate Change and Water (DECCW), National Parks and Wildlife Group manages the Sydney Harbour National Park which contains five of the eight Sydney Harbour islands. Two of these islands, Fort Denison and Goat Island are unique and of state and national heritage significance.

In order to manage these heritage assets effectively on behalf of the public for the benefit of future generations, DECCW's Coastal Unit were engaged to investigate the physical coastal processes impacting these sites and look at their vulnerability to projected sea level rise.

Whilst neither site is subjected to ocean swells, they are subjected to a broad range of local seas and boat wave climates from the multitude of vessels using this heavily trafficked portion of the harbour. This paper will summarise the detailed technical analyses undertaken to synthesise design still waters levels, wave climates and projected sea level rise to determine appropriate design ARI still water levels and wave run-up levels to 2050 and 2100 and their application for vulnerability assessment purposes.

The paper will discuss the key assets deemed vulnerable to sea level rise over various planning horizons, the likely impact on heritage values and public access at each site. In addition, the paper will canvass the engineering measures available to preserve and continue to access and utilise these iconic Australian heritage assets for as long as possible into the future.

1. 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 aboriginal, colonial and convict heritage.

Goat Island Goat Island is the largest of a number of sandstone islands sited in the central reaches of Port Jackson (DECC, 2007) within Sydney Harbour. The island has had a particularly unique and rich history which is evidenced by the many and varied heritage features which remain including an aboriginal midden, convict period structures and features, nineteenth century colonial buildings (including a Water Police station and gunpowder storage magazines) and twentieth century Sydney Harbour Trust and Maritime Services Board facilities (including a Harbour Master's residence, shipyards and wharfage) (DECC, 2007).

In recognition of their immense heritage significance and recreational values, Fort Denison and Goat Island (the majority of) were added to the Sydney Harbour National Park in 1995 and added to the State Heritage Register in 1999.

Perched in the middle of Sydney Harbour, both sites are subjected to the continual physical processes of winds, tides, waves and associated currents. Although not exposed to high energy ocean swells, these island sites are 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.

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

Figure 1.2: Aerial view Fort Denison (2008). Image courtesy Google Earth

Figure 1.3: Goat Island, Sydney Harbour. Photo courtesy DECCW.

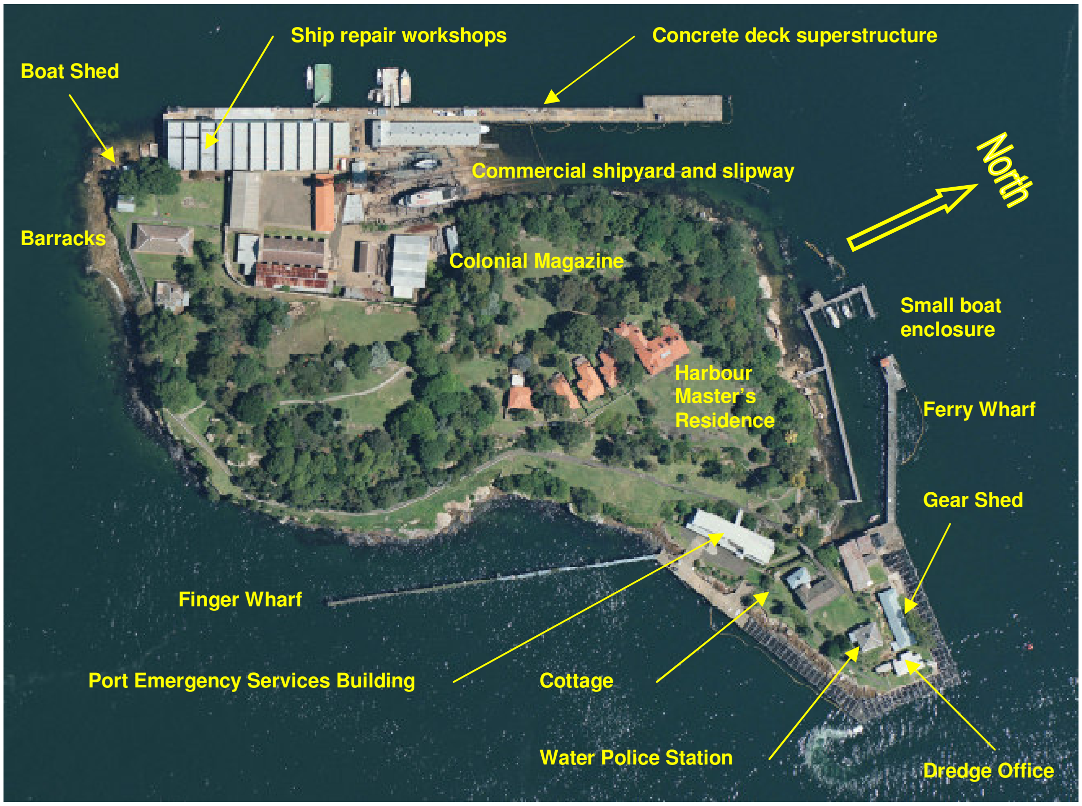

Figure 1.4: Aerial view Goat Island (4 March 2008). Image courtesy DECCW.

To date, both sites have generally withstood these constant processes reasonably well, with differential weathering of sandstone blockwork at Fort Denison the main casualty of the passage of time. At Goat Island the more exposed eastern side of the island is littered with disused wharves that have fallen into disrepair over time and which are now earmarked for demolition and removal. 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, utilisation and public accessibility of these facilities into the future.

The vulnerability studies undertaken by DECCW's Coastal Unit investigated the nature and extent of physical coastal processes including the impacts of projected sea level rise from climate change to 2100 to assist with long-term strategic planning and management of these iconic, heritage listed assets.

2. DATA SOURCES AND ANALYSES

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 and the quality of critical data sets necessary to analyse the projected impacts including: hydrographic survey data, land survey data, orthophoto imagery, historical water level data and wave data.

2.1 Survey Data

Despite the historical significance and age of both sites, there was extremely limited survey detail relating to levels of interest (including the crest and toe of revetments, 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 shoreline and/or toe of the external seawalls/revetments.

In early 2008, DECCWs Coastal Unit re-established pre-existing survey marks at both sites using GPS survey techniques. Conventional land based GPS survey techniques were employed to recover levels of all relevant land based features on each site including decks, floors, crests and toe of external seawalls/revetments, etc. These surveys were augmented with detailed hydrographic sonar surveys of the adjoining seabed and merged into seamless digital terrain models to produce detailed contour plans at both sites.

2.2 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 at either site, in particular Fort Denison, due to its diminutive size.

The Coastal Unit engaged AAMHatch Pty Ltd 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 resulting high resolution, low scale imagery was ortho-rectified to ground survey control points to provide baseplans fitted to the available survey data and co-ordinate grid system.

The ortho-rectified imagery provided 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 (refer Figure 2.1).

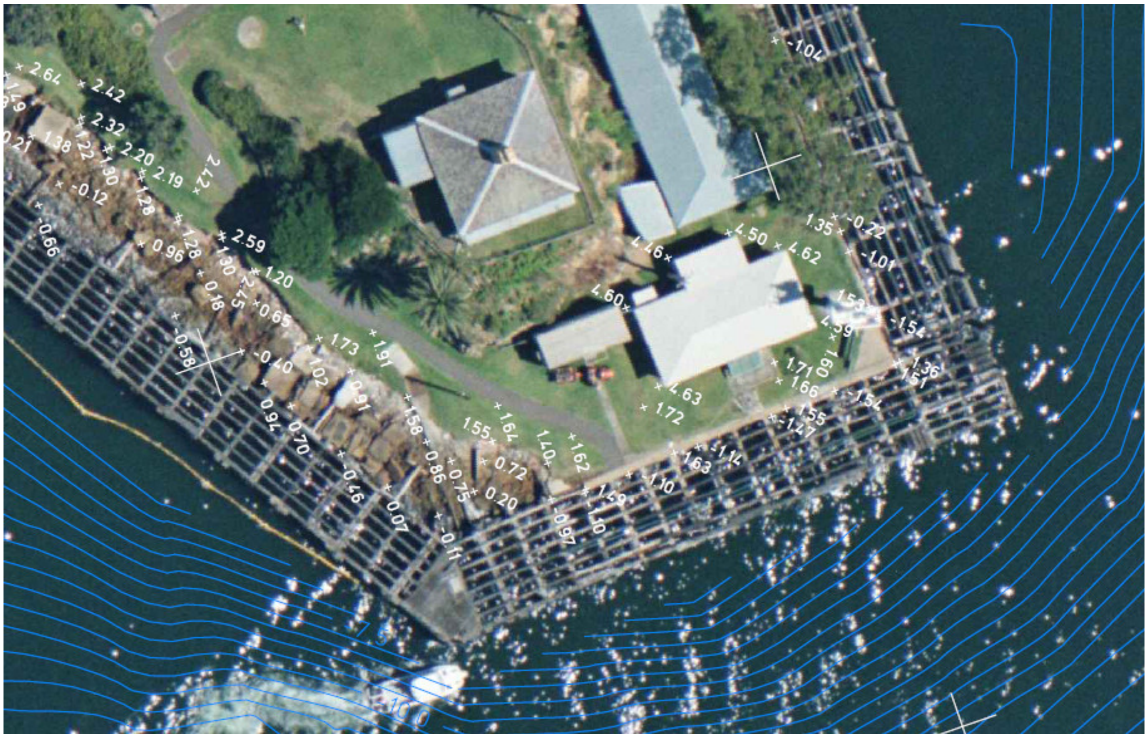

Figure 2.1: Extract from detailed survey plan of north-eastern corner of Goat Island within Water Police/South Depot Precinct (Levels in metres referenced to AHD).

2.3 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 rise over this timeframe (You *et al* 2009).

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 31st December 2006 to provide a summary of the normalised distribution of measured water levels for each cm graduation in height. Table 2.1 summarises the record high and low water level recordings at Fort Denison over this timeframe.

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. DECCW have undertaken 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 for various average recurrence intervals (ARIs). Relevant design levels are summarised in Table 2.2.

Table 2.1: 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).

Table 2.2: Sydney Harbour Design Still Water Levels (2008)

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 DECCW extreme value analysis (Gumbell Distribution).
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.

2.4 Wave Data

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). It is important to understand the nature of wave fields at each site in order to estimate the likely extent of wave runup and overtopping. Both sites are situated sufficiently inland from the ocean entrance not to be 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.

Although not subjected to ocean swell waves, both sites are 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.

The changing wind patterns and wide variety of boat wave signatures create wave fields approaching both sites 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 either site. 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.

Design wind wave climates (seas) were determined at each site based on conventional wave hindcasting techniques applied to wind data (Sydney Airport) for each of the primary orthogonal compass directions. 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. The largest wind generated waves impacting upon Goat Island are directed through the east toward the Water Police Station and from the south toward the Port Emergency Services Building and estimated to range in height up to 0.71 and 0.76m, respectively, with corresponding periods of 2.3 and 2.1s.

Unlike wind generated seas which 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. Although there are published procedures for estimating boat wave fields (Glamore, 2007), 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) were considered as the limiting case (refer Table 2.3).

Table 2.3: 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. (WP Geomarine, 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 (USACE, 2002) based on maxima values for wave height and period.

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 vulnerability studies, a representative or “equivalent” design wave climate was based on the maximum boat wave power combined with a nominal proportion (50%) of the maximum wind wave power 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 were then used in the form of a sensitivity analysis to determine maximum wave runup levels.

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

3. CLIMATE CHANGE AND SEA LEVEL RISE

3.1 Introduction

Of all the impacts from climate change, the projected rise in mean sea level is one of the most significant concerns for coastal zone managers. In addition to higher storm surge and oceanic inundation levels, a rise in mean sea level will also result in complementary 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, could 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 (Watson and Lord, 2008).

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

- Thermal expansion of the ocean;
- 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;
- Deposition of sediments on the ocean floor; and
- Changes in the mass of water stored in the terrestrial environment.

3.2 Measured Sea Level Rise

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.

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.

Over the operation of the TOPEX/Poseidon and Jason-1 altimeter missions (post 1992), average global sea level rise has been measured at approximately 3mm/yr (University of Colorado, 2009). 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 (IPCC, 2007). Nonetheless, when the altimeter data is synthesized with the longer-term tidal gauge records, there is a clear evidentiary trend of measured, increasing (albeit at low rates of) global average sea level rise.

3.3 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. 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. Importantly, IPCC (2007) advise that larger sea level rises cannot be excluded. 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. 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.

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).

Table 3.1 summarises the allowances used for the vulnerability assessment of both sites relevant to various planning horizons (2050, 2100) based on a synthesis of all information on projected sea level rise that was currently available at the time.

Table 3.1: 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. It should be noted that the analysis relating to sea level rise projections preceded the Draft NSW Government Sea Level Rise Policy Statement and advised planning benchmarks (February 2009), but are consistent with these values.

3.4 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 Table 2.2), have been synthesised with the respective sea level rise estimates in Table 3.1 to provide design still water levels incorporating sea level rise for various planning horizons (refer Table A1, Appendix A).

Figures A1 and A2 (Appendix A) graphically illustrate the indicative recurrence of various water levels under future sea level rise scenarios for 2050 and 2100 relative to the present, respectively. Similarly, Figures A3 and A4 (Appendix A) provide an indicative guide to the percentage of time design still water levels may be exceeded in 2050 and 2100.

4. 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 foreshores, seawalls/revetments, buildings and other marine infrastructure and assets around Fort Denison and Goat Island. For example, the crest level of revetments, jetties and paved areas adjoining foreshores, all provide direct references against which to assess the likelihood or extent of overtopping and oceanic inundation expected due to particular sea level rise scenarios over various future planning horizons.

The vulnerability assessment of both sites 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, coupled with an “equivalent” or representative design wave climate to estimate wave runup ($R_{u2\%}$) levels. This analysis has been carried out at key locations around each site for each planning horizon using procedures in the Coastal Engineering Manual (USACE, 2002).

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. The design runup levels advised provide an indicative estimate of the height to which seawater may rise after breaking against the shoreline or associated foreshore structures and seawalls.

5. CONCLUSIONS

5.1 Fort Denison

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 5.1).

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 5.1: 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.

5.2 Goat Island

The majority of built assets on Goat Island are elevated sufficiently beyond the threat of tidal inundation and associated wave runup and projected sea level rise over the course of the this century. Notwithstanding, it is clear that the Boat Shed and North and South Depot Precinct foreshores are already vulnerable to tidal inundation and wave runup, which will be exacerbated by any form of sea level rise into the future. Founded below 1.0m AHD, the Boat Shed is currently inundated with seawater on general spring tides accompanied by any boat or wind wave action.

Elevated at a mere 1.35m AHD, the lowest foreshore and vertical retaining wall crest levels within the North and South Deport Precincts could be overtopped with seawater to a depth of 7cm under a “HIGH” sea level rise scenario by hourly still water levels in 2050 that would occur as often as 20 times per year (in the absence of waves). Similarly by 2050, the lowest crest level within these precincts would be overtopped by still water levels to a depth of at least 26cm on an annual basis under a “HIGH” sea level rise scenario.

Figure 5.2: Foreshore recession and failed ad-hoc protection works in South Depot Precinct

In addition to the threat from inundation due to still water levels, wave climates discharge energy against foreshores, wharfage and retaining wall structures around the Island resulting in seawater being elevated to significant heights. The current design 100 year ARI wave runup levels would exceed the lower crested retaining wall structures at the exposed north-eastern corner of the Island by as much as 2.5m. With projections for future sea level rise, these structures will become increasingly more vulnerable to wave runup and overtopping over time.

On current projections, the Boat Shed and comparatively low foreshore areas within the North and South Depot Precinct areas will be significantly impacted upon by sea level rise by 2050. It is likely that the current configuration of assets within these areas could continue to be effectively managed with minor modifications (higher crested, improved foreshore protection structures where necessary) to combat a modest rise in sea level of possibly 10-20cm. This would include provision of a seawall structure to an appropriate engineering standard to replace the ad-hoc rubble and concrete slabs currently in place to control erosion along the foreshore between the Port Emergency Services Building and the Dredge Office (refer Figure 5.2). The incorporation of innovative design practices and wave deflector capping to limit potential wave runup and overtopping, would be sufficient to manage current threats and sea level rise projections to 2050. Similarly the vertical retaining wall structures extending from the Dredge Office to the Fire Fighting Building would need to increase crest heights and incorporate wave deflector capping to manage the threat of wave runup and projected sea level rise over this timeframe.

Beyond 2050, larger projected rises in mean sea level may eventually compromise the useability and general accessibility of these lower foreshore areas due to the scale of capital works required to mitigate the threat of seawater inundation. It is also recommended that all existing and planned future wharfage infrastructure around the Island be upgraded to floating pontoon style systems to more adequately accommodate sea level rise into the future.

By 2100 under a “HIGH” sea level rise scenario, all foreshore structures (including wharves, decks and jetties) around the island are projected to be submerged by seawater with an ARI of 10 years or more. This is of particular importance for commercial leasehold operations within the Shipyard Precinct. In this regard, it is strongly recommended that any planned maintenance or future upgrades to existing built infrastructure within this Precinct take full consideration of the implications of sea level rise at the planning and design stages.

5.3 General

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. 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 both sites, which are vulnerable to climate change induced sea level rise can be guided by the implications of the advice contained within the detailed vulnerability studies undertaken 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.

At the time of writing (September 2009), the complete reports were publicly available at:

http://sydneyharbourpom.net.au/

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APPENDIX A

Table A1: 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 2.2.
2. L, M and H refer to Low, Medium and High projections for sea level rise. Corresponding allowances derived from Table 3.1.

Figure A1: Projected 2050 Design Still Water Levels

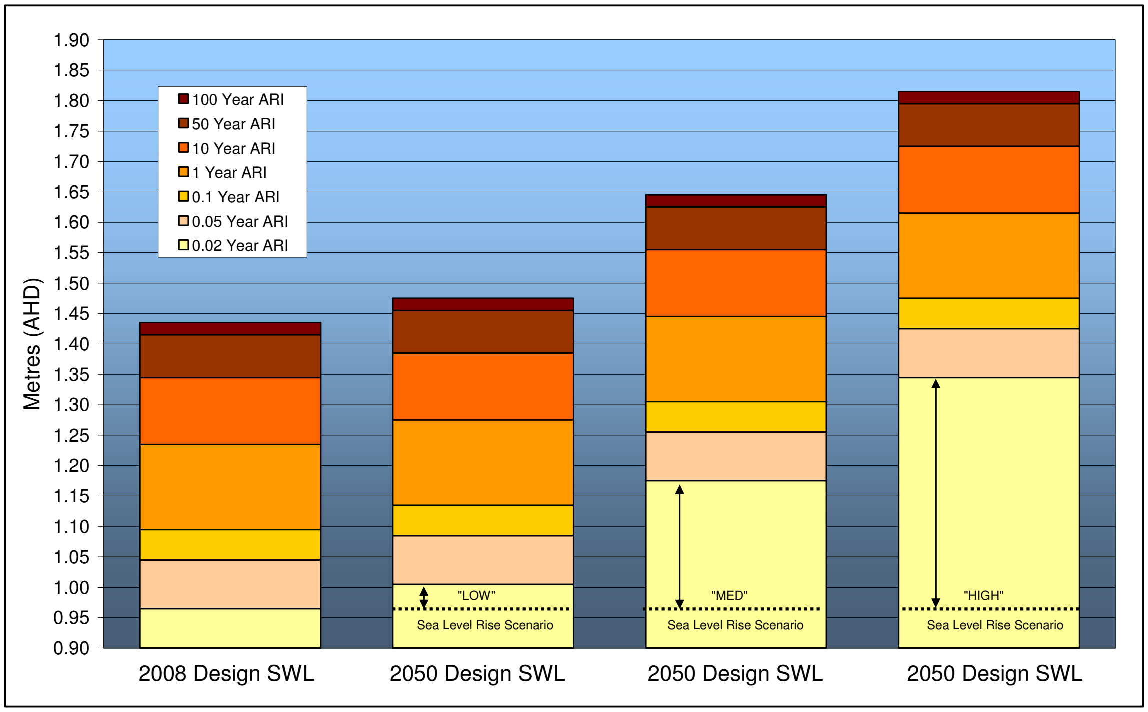


Figure A2: Projected 2100 Design Still Water Levels

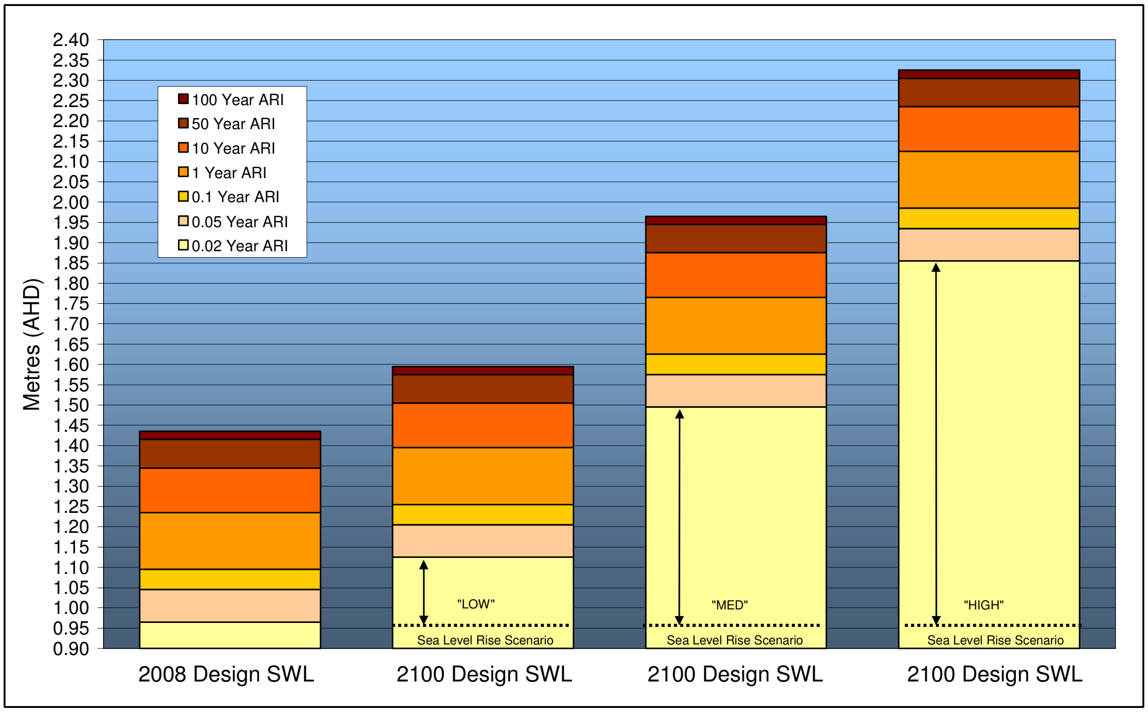
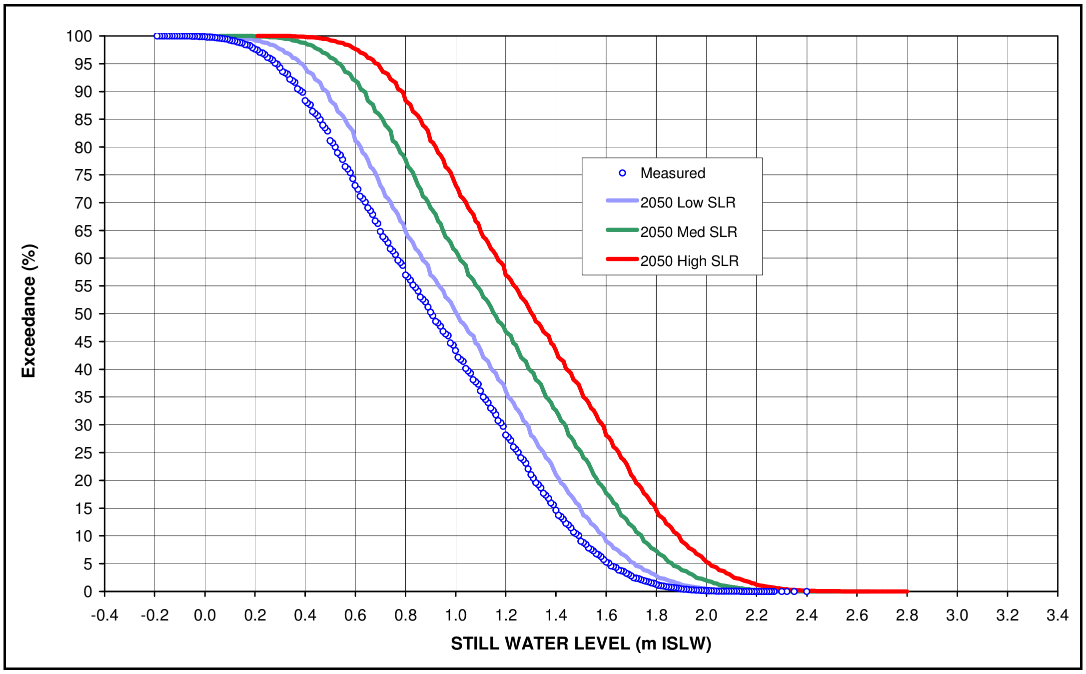
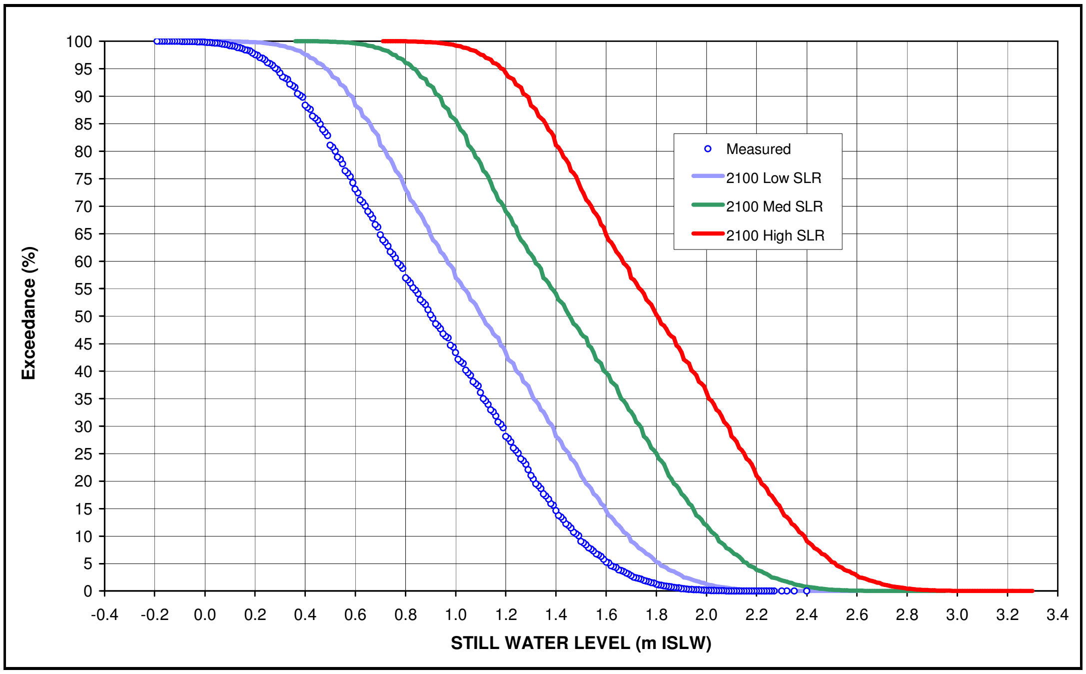


Figure A3: Sydney Harbour Water Level Exceedance (2050)



Notes:
1. Measured values derived using Fort Denison data from 31 May 1914 to 31 December 2006.
2. 2050 projections based upon the addition of “Low”, “Med” and “High” sea level rise estimates using the recommended planning allowances advised in Table 3.1.
3. For conversion from ISLW to AHD, subtract 0.925m.

Figure A4: Sydney Harbour Water Level Exceedance (2100)



Notes:
1. Measured values derived using Fort Denison data from 31 May 1914 to 31 December 2006.
2. 2100 projections based upon the addition of “Low”, “Med” and “High” sea level rise estimates using the recommended planning allowances advised in Table 3.1.
3. For conversion from ISLW to AHD, subtract 0.925m.