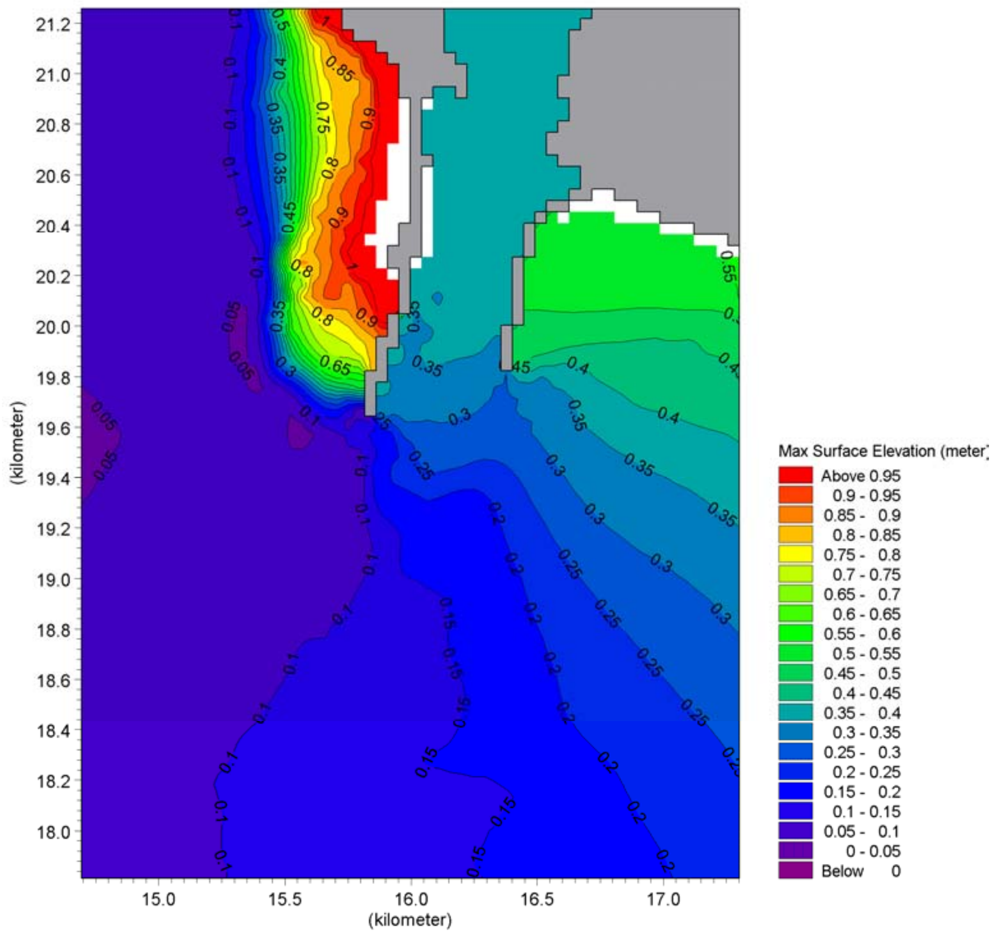
Analysis of Extreme Ocean Water Levels at the Hunter River Entrance

Technical Report



Newcastle City Council **June 2008**

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APPENDICES

1 EXECUTIVE TECHNICAL SUMMARY

1.1 Purpose

The Newcastle Local Government Area is exposed to flooding from a range of sources. The most recent floods of June 2007 and February 2008 provided a stark reminder of the exposure of parts of the city to flash flooding generated by intense rainfall over the local city catchment. Parts of the city, especially in the western suburbs around Hexham Swamp are also exposed to riverine flooding from the Hunter River. These floods, which are generated by broader scale storm systems over the wider Hunter River catchment, are best exemplified by the well remembered flood of February, 1955.

Along with floods generated by rain producing storm events of various scales, it is also recognised that flooding of the lower floodplains of the Hunter River, including the lower parts of the city area near Throsby and Cottage Creeks and Hexham Swamp, are also potentially exposed to flooding by an elevated ocean level event or "storm surge".

The purpose of this technical report is to provide an assessment of the various extreme ocean phenomena which may induce an elevated ocean level and to quantify estimates of the component ocean water level anomalies that might combine to develop into an elevated ocean level or "storm surge" event in the extreme range.

The information presented in this report will assist floodplain managers to make informed planning decisions in areas impacted by extreme elevated ocean levels. The elevated ocean level information provided is presented in a form which will allow floodplain managers and planners to select elevated ocean level anomaly components to combine into boundary conditions for ocean storm surge flood scenarios relevant to decisions influenced by flood exposure at the extreme end of the risk and hazard scale.

It is important to note that the investigations undertaken in compiling this report are particular to the Hunter River entrance and estuary. While the ocean level phenomena investigated are common to the NSW coastline, the levels quoted in this report are influenced by the local shape, form and depth of the Hunter River entrance and estuary and for this reason may not be applicable to other sites.

1.2 Study area – the reach and response of the Hunter River estuary to elevated ocean levels

While not definitive, the tidal limit is indicative of the reach of fluctuating ocean levels up the Hunter River estuary. The tidal limit of the Hunter River is somewhat variable, being influenced by the volume and level of sedimentation in the river channel. At the time of compiling this report, the water level recorder upstream of Maitland at Oakhampton, some 55km from the Hunter River ocean entrance, was showing a tidal influence at high tide (MHL, 2008).

The zone in which extreme elevated ocean levels dominate the peak flood level envelope is, however, more limited. Peak flood levels generated for an extreme range

Hunter River flood such as the Probable Maximum Flood (PMF) event show that river flood levels are expected to dominate at this end of the risk scale upstream of Walsh Point on Kooragang Island (DHI, 2007).

The study area for this ocean level analysis report focussed on providing representative data for those areas of the Hunter River estuary dominated by ocean phenomena under extreme flood conditions. This area is indicated in Figure 1-1. The representative sample location used for reporting ocean level anomalies is indicated by the white dot.

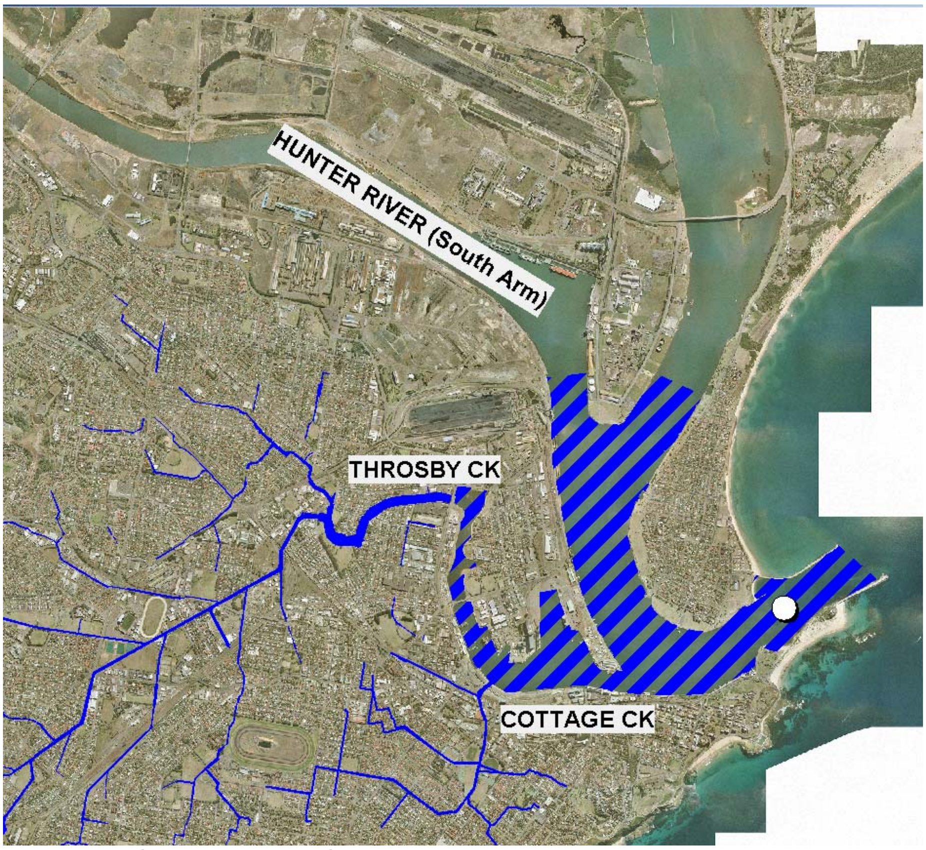

Figure 1-1 –Study Area (Blue Stripe)

1.3 Physical Processes Summary

There is a range of different oceanographic processes that can influence water surface levels in Newcastle Harbour and the Hunter River estuary. These oceanographic phenomena can be grouped broadly as those processes which occur independently of each other and those which occur in association with a storm event offshore of the NSW central coastline.

Independent oceanographic phenomena are identified as:

- Astronomical tides;
- Long term sea level rise; and
- Other effects such as El Niño Southern Oscillation (ENSO), coastally trapped waves, and steric effects;

Storm dependant phenomena include:

- Barometric effects;
- wind set-up effects; and
- Wave set-up effects;

Astronomical tides are periodic and completely predictable in advance, however none of the other phenomena are astronomically periodic and there is uncertainty in estimating possible scenarios, especially worst case (extreme) scenarios.

Storm surge is the combination of increased water levels balancing reduced atmospheric pressure (**barometric effects**) adding to on-shore winds "pushing up" average water levels at the coast line (**wind set-up**). Storm surge would be expected to propagate with very little reduction well into the harbour and estuary since the forcing phenomena cover large areas and may last for several days.

The influence of **wave-setup** is dependent on the local conditions of the area because of the significant influence of bathymetry on local wave conditions. Newcastle Harbour is a deep water port with a narrow entrance which rapidly reduces the impact of wave set up with increasing distance from the harbour entrance. As a result wave set up is not as significant as at other more open locations on the NSW Coast.

Predictions of **long term sea level rise** have been provided based on NSW Government guidelines. These predictions have used Intergovernmental Panel on Climate Change (IPCC) projections, adjusted for local conditions, and should be updated when IPCC estimates are revised from time to time.

The understanding of **other effects** resulting from many different oceanographic and meteorological factors such as ENSO and coastally trapped waves has been made possible by recent advances in remote (satellite) sensing and can be significant contributors to elevated harbour levels. More information on these processes is provided in the body of the report.

1.4 Results Summary

The results tabulated in Table 1-1 are indicative of the anticipated maximum water level of each oceanographic phenomena considered, at the extreme end of the risk probability scale.

In this form, the tabulated components provide the floodplain manager with a guide as to the appropriate constituent values that can be combined to produce an extreme elevated ocean level scenario.

Additional background information describing the derivation of the tabulated values is provided in the body of the report.

Table 1-1 Summary of Extreme Ocean Levels at Newcastle Harbour

Conditions	Phenomenon	Water Levels
Extreme Storm	Storm surge and wave set-up	0.8m +0.1m 0.9m
Coincident with one or more independent phenomena	Astronomical tide Steric effects Climate influences Coastal trapped waves	up to 1.1m AHD* 0.1m 0.1m 0.3m
Plus climate change effects	Sea level rise at 2100	0.18 -0.91m**

* high range is HAT

** dependent on planning horizon and climate change scenario

Floodplain managers are required to make informed decisions regarding the combination of phenomenon included in the individual scenarios for analysis. Extreme joint probability should be considered if adopting storm conditions plus one or more independent phenomenon. Inclusion of sea level rise will essentially be a planning decision made by the floodplain manager.

2 INTRODUCTION AND GENERAL BACKGROUND

Newcastle City Council (NCC) engaged DHI Water & Environment (DHI) to undertake an assessment of extreme elevated ocean levels at the Hunter River entrance with the aim of developing a data set to enable flood planning investigations to define the areas of the Newcastle local government area exposed to flooding by extreme elevated ocean level events. A second use of the data set is to enable floodplain managers to set appropriate tailwater levels for extreme flood analysis using computer modelling techniques.

Elevated water levels can occur along a coastline through the influence of a range of different phenomena including:

- Astronomical tides;
- Storm surge (barometric effects and wind set-up effects);
- Wave set-up effects;
- Greenhouse effects; and
- Other effects, such as ENSO (El Niño Southern Oscillation), shelf waves, etc;

The nature of these phenomena and the specific coastal features at a particular location will determine the net magnitude of each effect. Background information on these processes follows.

2.1 Astronomical tides

Coastal water levels fluctuate in a regular and predictable fashion in response to the gravitational effects of the moon, sun and planets on the oceans of the earth. The tidal range varies from tide cycle to tide cycle in response to the ever changing relative positions of these bodies. However, the tidal range undergoes a regular fortnightly cycle, increasing to a maximum over a week (Spring Tides) and then decreasing to a minimum over the following week (Neap Tides), because of the monthly orbit of the moon around the earth. Solstice tides, or King Tides occur in June and December of each year, when the sun is directly over the Tropics of Cancer and Capricorn respectively.

Tides along the New South Wales coastline are semi-diurnal in nature, i.e. high water and low water occur about twice daily (the actual period of a tidal cycle is about 12.5 hours). They are sinusoidal in shape and generally have a pronounced diurnal inequality (successive high tides usually differ markedly). The Highest Astronomical Tide (HAT) in Newcastle has been calculated as 2.1m (refer to local tide datum) or 1.1mAHD. This value occurs approximately every 18.6 years. However, very high tide levels in the order of 2.05m to tide datum or 1.05m AHD typically occur a few times each year.

2.2 Storm Surge

Storm surge events, also known as inverse barometric effect, are produced by the combined effects of falling atmospheric pressure and intense winds due to severe weather events. Typically the increase in water level attributed to inverse barometric effects amounts to approximately 0.10m for each 10hPa drop in atmospheric pressure. On coasts fronted by wide continental shelves the larger contribution is due to wind stress acting on the surface of the ocean, effectively “piling up” water against the coast, however this is not the case in NSW. The period of occurrence of these effects can range from a few hours to several days. For example the 1974 ocean storm surge event lasted for 5-6 days. The area influenced by an inverse barometric event can be large and is related to the intensity and reach of the low atmospheric pressure system causing it.

In available literature, there is some confusion between the definition of a storm surge and storm tide with each term being used interchangeably depending on the particular context. Generally a storm surge is the elevation of water generated by a storm system above the normal astronomical tide. A storm tide is however, the total elevation which includes the astronomical tide above a specific datum.

Storm tide can also be defined to include wave set-up and run-up. Wave set-up is the super elevation of the nearshore water level due to wave breaking, while wave run-up is the ultimate height reached by individual waves when they arrive at the shoreline.

Storm surges can be successfully determined through the use of computer modelling techniques, however the storm tide can be difficult to predict due to phasing uncertainties with the astronomical tide. It is this storm tide which is the predicted elevated water height issued in tropical cyclone advisories. As the total storm tide consists of non-linear components, they all both affect and are affected by changes in water level. As a result an infinite number or combinations of storm surges, tide and wave set-up are possible to produce variations in storm tide level.

There are a number of factors which can influence the height of a storm surge such as the range of possible spatial scales, and ocean responses to severe low pressure systems. The effects of these factors can be quite different in deep and in shallow water. A narrow continental shelf, or one that drops steeply from the shoreline and subsequently produces deep water in close proximity to the shoreline tends to produce a lower surge, but a higher and more powerful wave. In contrast, coastlines that have long, gently sloping shelves and shallow water depths are subject to higher storm surges but smaller waves.

In deepwater, the surface wind stress from a tropical cyclone creates a rotating vortex of water by diffusing momentum downward and away from the system. The ocean elevation is small; approximately the hydrostatic uplift in response to the low central pressure (the inverted barometer effect). As the system approaches the shallow waters of the continental shelf, conservation of the potential vorticity of the mound requires development of marked divergence. The surge cannot be dispersed away and is driven onshore by the wind stresses of the system. Channelling by local bathymetry, the proximity to bays, headlands and islands as well as reflections from the coast can also all contribute to substantially amplify the height of the surge.

2.3 Wave set-up

Water levels at a particular location can also be influenced by wave processes, which vary depending on the local bathymetric characteristics of the site. Wave breaking produces wave setup, which is super elevation of mean water level resulting from the mass transport of water into the surf zone. The amount of wave setup at a particular area, such as the Hunter River entrance, will vary depending on the exposure of the site to wave energy, the persistence of the wave energy, as well as on the character of the entrance, including minimum water depths and the presence of training works.

Most of the previously mentioned processes that induce increased water levels can be evaluated at a regional scale, whereas the influence of wave induced set-up is perhaps the most difficult to determine because of the significant influence of bathymetry on local wave conditions; an overview of the Hunter River entrance is presented in Figure 2-1 below.

In this study a detailed analysis of the wave setup was undertaken to evaluate the local effect on water levels at the Hunter River entrance.

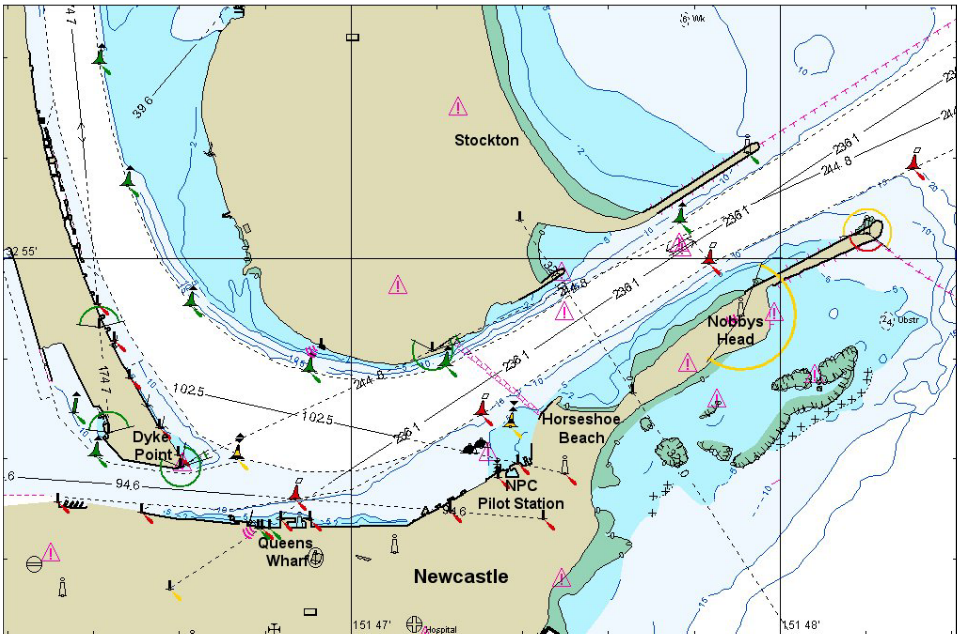

Figure 2-1 Overview of the Hunter River (harbour) entrance area.

2.4 Climate change effects

Sea-level rise is one of the projected outcomes of climate change documented in the three successive reports over the last decade by the Intergovernmental Panel on Climate Change (IPCC). The IPCC's main objective was to assess scientific, technical and socio-economic information relevant to the understanding of human-induced climate change, potential impacts of climate change and options for mitigation and adaptation.

The NSW Department of Environment and Climate Change (DECC) has reviewed the IPCC (2007) reports and produced a floodplain risk management guideline document "DECC FRM Guideline: Practical Consideration of Climate Change" (DECC 2007). This document identifies that IPCC predicted sea level rise trends on the NSW coastline may fall in the range of 0.18m to 0.91m by 2090- 2100.

2.5 Other Factors that may affect water levels

Recent advances in remote sensing techniques enable scientists to produce high resolution maps of the sea level and geostrophic current velocities. Such information is collected by satellites carrying radar altimeters that measure the distance from the satellite down to the water. An example of these observations is presented in Figure 2-2.

The left hand panel on Figure 2-2 shows residual sea level anomalies that have been adjusted for the relatively rapid variations of the inverse barometric effect and tidal oscillations. The atmospheric pressure map used for making the isostatic adjustment is shown in white as features of the circulation (e.g. near the coast, or under a tropical cyclone) can sometimes be explained by the winds. Tidal information is included in the maps by averaging out the tides, making the same atmospheric pressure calculation as with the altimeter estimates, and then interpolating the results at many points along the coastline between the gauges. Both the observed and interpolated coastal observations are shown on the map.

The right hand panel on Figure 2-2 shows sea surface temperature anomalies plus a hydrographic estimate of the mean sea surface shown in white contour lines. Black arrow heads depict the direction and strength of the ocean currents.

Varying sea levels are a result of many different oceanographic and meteorological factors which can have a marked effect at the coast. Such disturbances vary spatially and temporally and can be difficult to predict, trace and measure. Tsunami impacts are outside the scope of this Study, but factors that are relevant include:

- Variations in salinity and temperature (known as steric effects);
- Major meteorological phenomena such as the El Nino Southern Oscillation (ENSO) which can affect water levels along the NSW coastline;
- The influence of strong currents such as the Eastern Australian Current which moves south along the coast and can cause eddies; and
- Coastally trapped waves which are produced by meteorological disturbances that are characterised by a sharp pressure gradient.

It should be noted that while these phenomena may add to a sea level rise event, they are independent of the type of storm event that would specifically produce a storm surge in Newcastle Harbour.

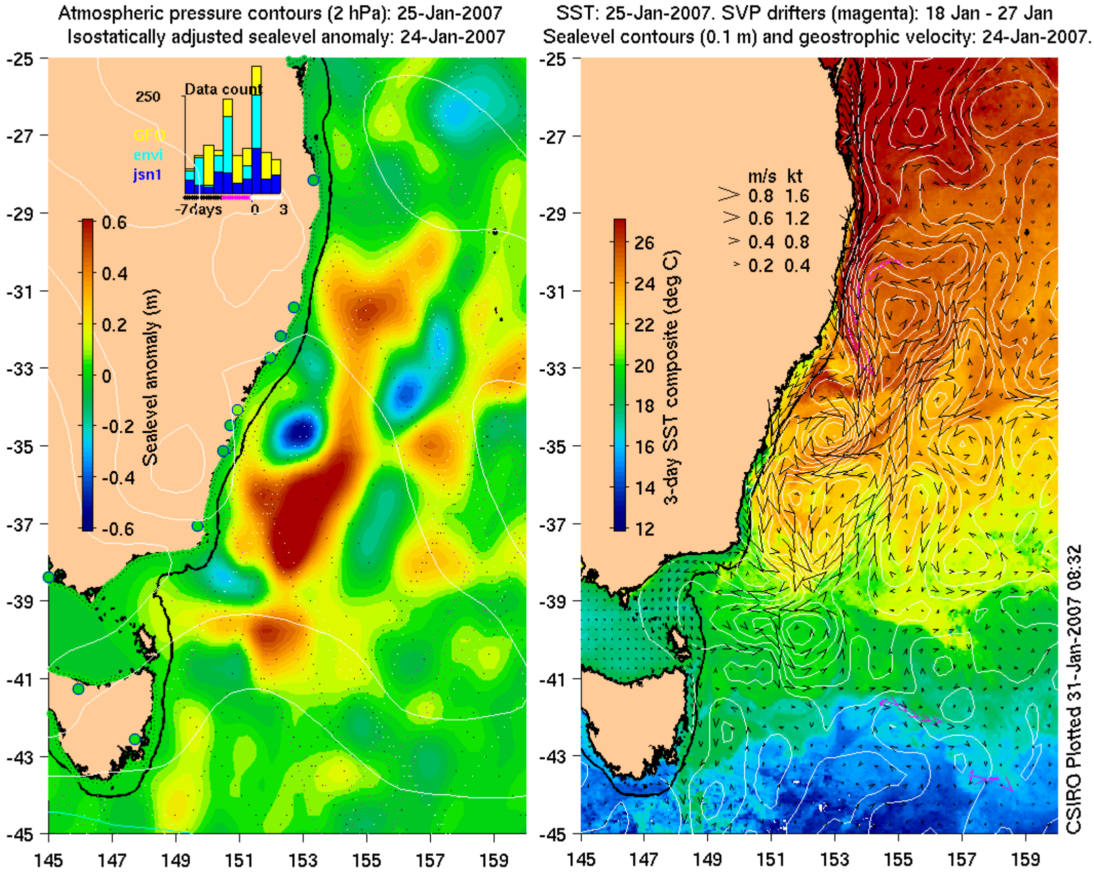

Figure 2-2 Observed sea level anomalies and sea surface temperature and current speeds (from www.marine.sciro.com.au/bluelink)

2.6 Historical Water Levels in the Sydney Region

The availability of data for Fort Denison since 1914 provided an opportunity to re-evaluate the data and employ a combined storm tide analysis. Wyllie et al (1993) undertook statistical analysis of water levels in the NSW coastal tide record and found that anomalies of up to 0.4m are very common on the NSW coast as shown in Table 2-1 below.

Anomalies are defined as the difference between predicted and recorded tide levels and are the result of the range of sea level rise phenomena such as storm surge, wave set-up etc discussed above.

Table 2-1 Sydney Harbour Tidal Anomaly Distribution 1914-1991 (from Wyllie et al 1993)

Level (m)	Return Period (Years)
0.60	76
0.50	2
0.40	0.2
0.30	common
0.20	common
0.10	common
0.00	common
-0.10	common
-0.20	common
-0.30	0.2
-0.40	4
-0.50	76

These data show that anomalies of 0.6m and 0.5m, which can be attributed to significant barometric effects and wind set-up, have return periods of 76 and 2 years respectively. These data provided additional understanding on storm surge whereby the belief that storm surges recorded at a site can be directly correlated to the local barometric pressure and wind conditions was shown to be a poor assumption. A surge recorded by the Public Works Department (April 1990) showed that intense low pressure in the southern Tasman Sea and Bass Strait, can develop tidal anomalies along the south and central NSW coast when the local atmospheric pressure is not unusually low. The April 1990 surge was the third largest anomaly recorded since 1914 and increased the ocean levels from Eden to Port Stephens approximately 0.4m above the predicted tide. This compares to the May 1974 storm which generated an anomaly of 0.6 m and a peak level of 2.37m (1.46m AHD), above gauge zero. This analysis considered all hourly data points over the 1914-1991 period and generated the frequency distribution of the astronomical tide and storm surge. An example of the results adopted for previous studies such as the Broken Bay Beaches Coastal Processes Study, (Patterson Britton and Partners, 1998) is shown below.

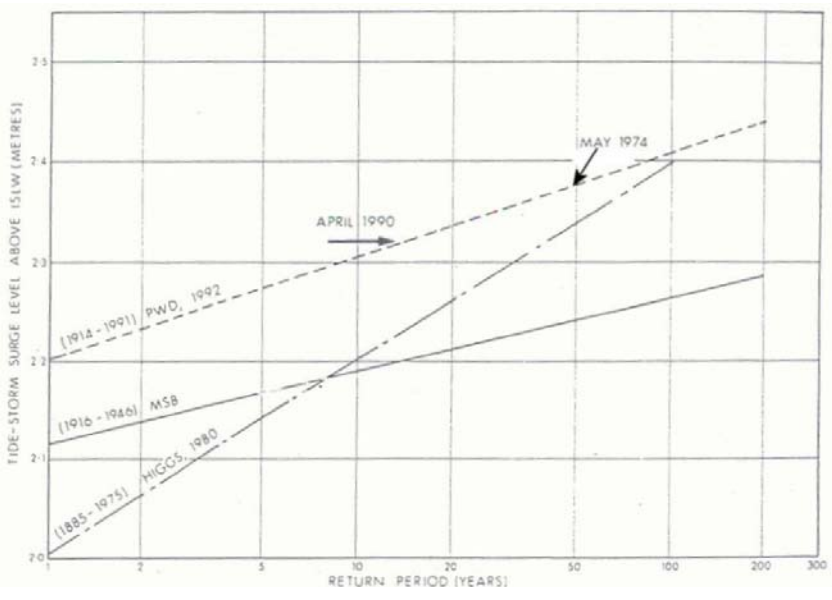

Figure 2-3 Design ocean levels for Fort Denison

On the basis of these analyses, the 100year return period elevated ocean water level is 1.5m AHD and the 200 year return period elevated ocean water level 1.8m AHD.

3 REVIEW OF EXISTING INFORMATION

A literature review of relevant existing reports and an analysis of available data for the study area have been completed. The data review evaluated available bathymetric information and offshore wave data for the area, and flow conditions in the Hunter River entrance as well as a review of previous relevant study reports.

The data review provided the basis for defining model bathymetry and the offshore wave conditions to be modelled and analysed. Analysis of the available base data leads to the definition of various scenarios used to evaluate elevated ocean levels at the Hunter River entrance in general and wave induced set-up processes in particular.

3.1 Bathymetric Information

Bathymetric surveys and beach profile measurements of the area have been obtained from the Department of Environment and Climate Change (DECC formally Department of Natural Resources). Hydrographic data in the study area were provided from surveys completed in 2002. Figure 3-1 shows the 2002 bathymetric survey that extends 8 km from SW to NE and 7.5km from NW to SE (shown as light blue points).

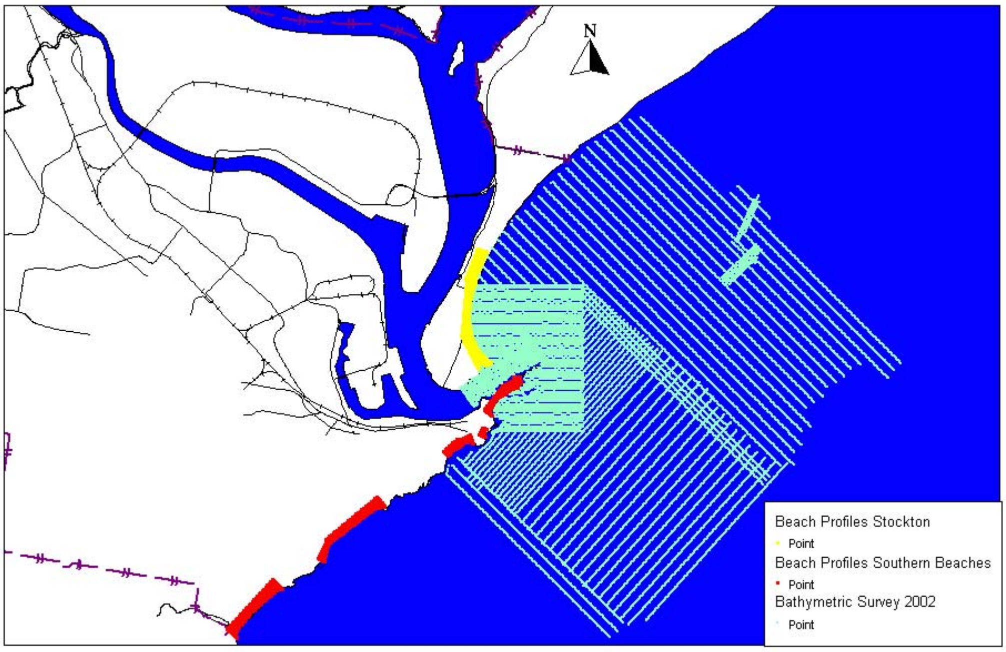

Figure 3-1 Overview of the 2002 bathymetric survey.

3.2 Wave Data

Offshore wave measurements at the Sydney (directional) wave rider buoy have been analysed. The Sydney wave data were used as this buoy is the closest instrument to the Hunter River entrance that measures directional wave data. A wave rose for the period

1992-2004 is presented in Figure 3-2. The analysis results show that the most frequent and largest waves in the record propagate from the SSE direction. These waves originate in the Southern Ocean and propagate as ocean swell toward the study area. Waves from the E and ENE are also frequent and associated with large storm events and cyclones in the Coral Sea.

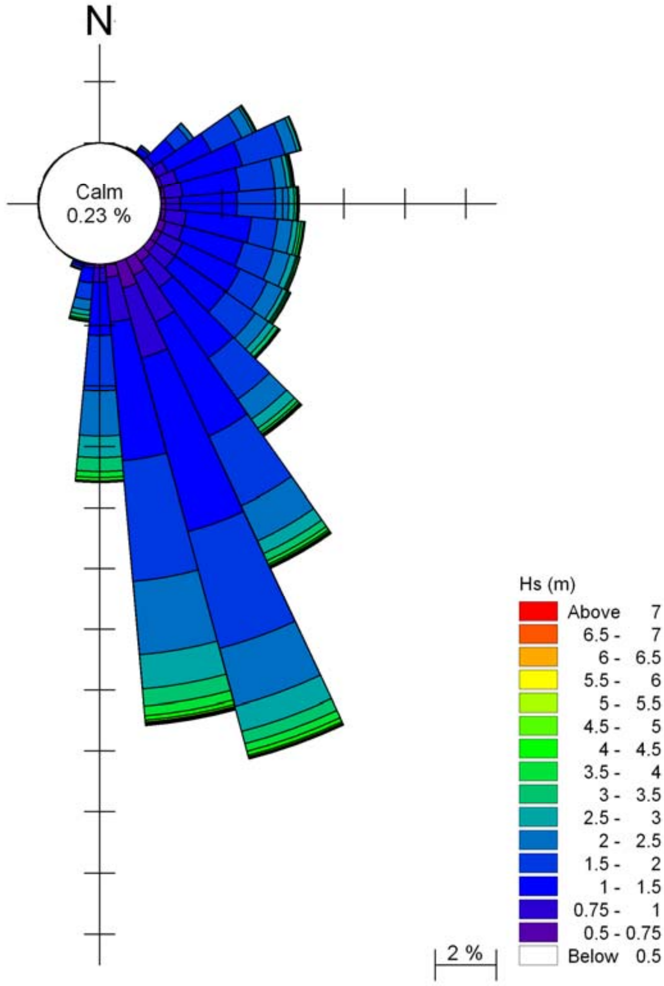

Figure 3-2 Wave rose at the Sydney waverider buoy for the period 1992-2004

Extreme wave conditions have been estimated based on statistical analysis of the Sydney wave rider buoy data. The statistical analysis presented is based on a presentation of significant wave height (Hs). Significant wave height is approximately equal to the average of the highest one third of waves in any sampled period. As an average statistic, the value of Hs tends to reduce with the length (period) of record considered, e.g. an Hs estimate for a 1 hour period is typically greater than an Hs estimate for 24 hour period which includes the same 1 hour period sample.

Wave rider buoys, which are the source of wave data, typically do not measure wave heights continually, rather they record in bursts of a minute or two minutes duration several times an hour. A wave height return period curve produced by analysis of this burst data and extrapolated into the extreme range on the basis of data presented in Lord and Kulmar (2000) is presented as Figure 3-3. The extrapolation into the extreme range in Figure 3-3 provides an extreme wave Hs for the 10,000 year return period of 14.2m. Due to the bathymetric conditions of the area it is considered that larger waves are unlikely as offshore waves tend to dissipate due to breaking and friction.

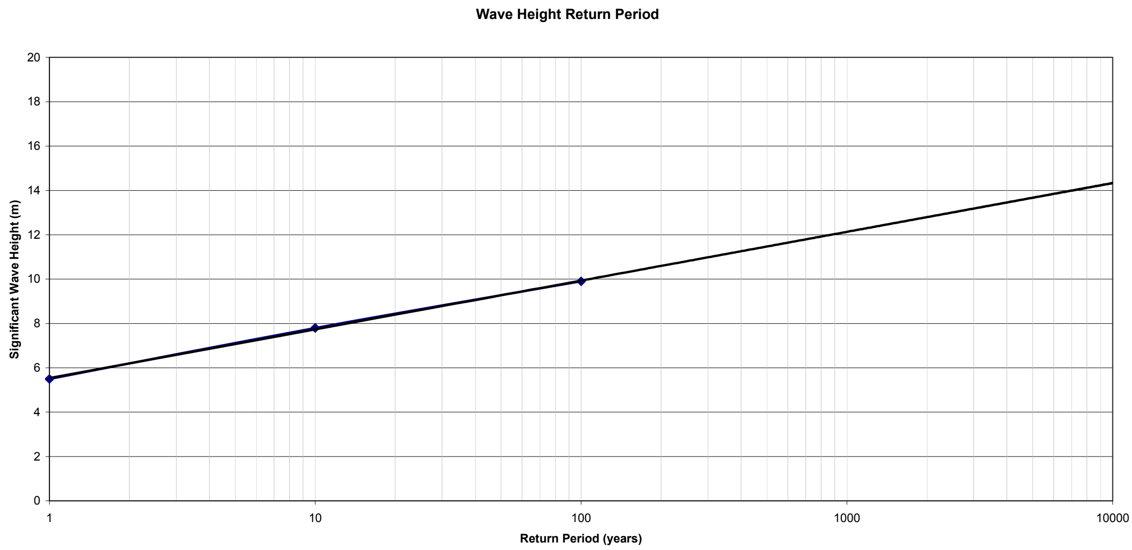

Figure 3-3 Wave height recurrence intervals for the Sydney area using" burst" data.

Lord and Kulmar (2008) provides some analysis of wave height statistics with duration for the period available for the Sydney waverider buoy from 17 July 1967 to 31 December 1999. A summary of Hs versus duration from this paper is provided in Table 3-1.

Table 3-1 Sydney Significant Wave Height versus Analysis Period – 100 year return period

Analysis Period (hours)	100 year Hs (m)
1	8.6
6	7.5
12	6.7
24	6.3
"instantaneous"	10.0 (see Figure 3-3)

The summary in Table 3-1 compares to the analysis of the "burst" sample wave data which gives an Hs for the 100 year recurrence interval of 10.0m, as shown in Figure 3-3. The "burst" analysis in Figure 3-3 could be thought of as an instantaneous maximum, while the data in Table 3-1 represents time averaged maxima.

The duration of the wave Hs applied, along with the influence of other ocean phenomena on elevated ocean levels, needs to be chosen in the context of the response of the particular site being analysed. By way of explanation for floodplain managers, the selection of an appropriate Hs value is analogous to the process of choosing an appropriate design storm duration to estimate maximum flooding conditions from catchment runoff.

Preliminary modelling analysis indicated that the Newcastle Harbour entrance area responded quickly to changes in ocean level. Therefore for analysis of extreme ocean levels around Newcastle Harbour entrance area, the "burst" analysis data (with an extreme wave height of Hs=14.2m) is considered appropriate. For other parts of the estuary, a longer duration would be required to set-up water levels in response to elevated ocean waves, so a reduced Hs value should be adopted for analysis e.g. in the order of Hs=10m for durations of 6-12 hours or more.

It should be noted that this conclusion is site specific to the Hunter River entrance at Newcastle. Other river entrances and lagoons on the NSW coastline may respond differently and warrant the use of a longer duration wave statistic.

3.3 Tidal Water Levels Information

Tidal water levels have been predicted for the Newcastle Tidal Station on the basis of tidal harmonic constants obtained from the Australian National Tide Tables Handbook Commonwealth of Australia, Department of Defence (2003). Figure 3-4 shows the water level predictions for 2006. Tides in Newcastle are semidiurnal with a maximum amplitude of approximately 2m.

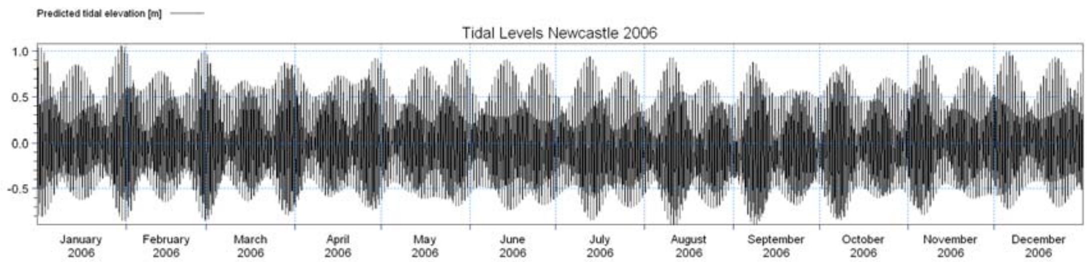

Figure 3-4 Predicted water levels at the Newcastle Pilot Station during 2006.

An exceedance curve of water levels at Newcastle Harbour for a full lunar cycle of 18.6 years has been produced based on tidal predictions based on the handbook. An exceedance curve for this data is presented in the Figure 3-5 below.

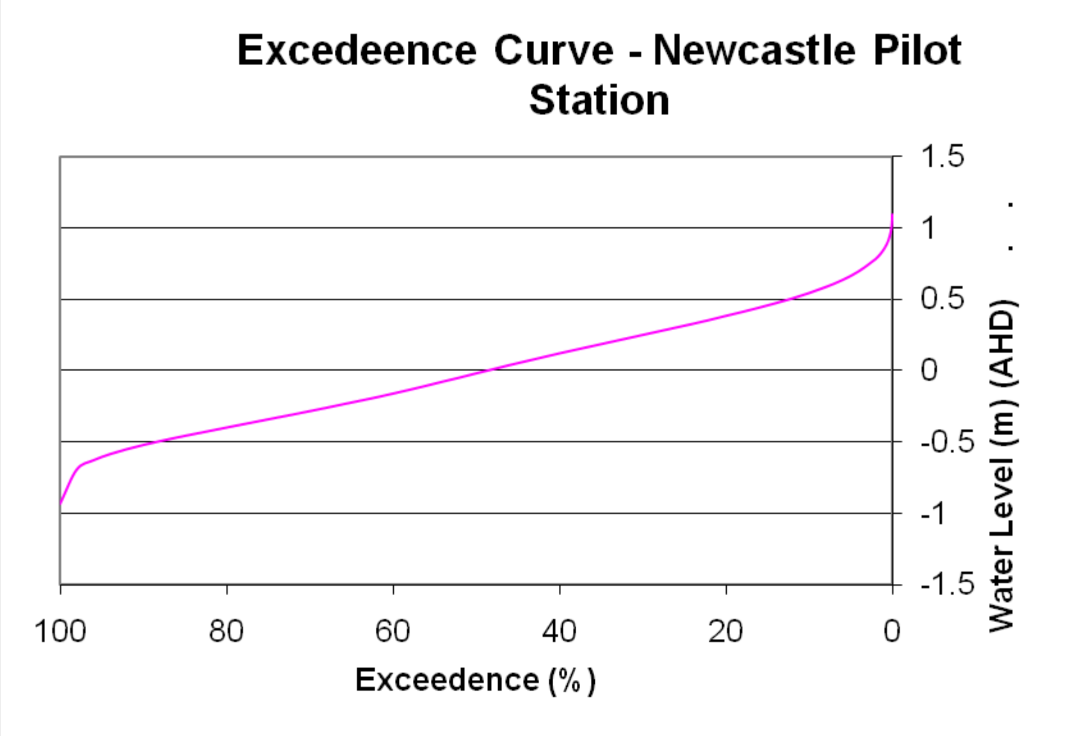

Figure 3-5 Astronomic (Tidal) Water level exceedance curve for the predicted tide at the Hunter River entrance – Newcastle Pilot Station.

A summary of tidal water level statistics for Sydney and Newcastle is presented below:

Tidal levels at Fort Denison are (referred to MSL):

Highest astronomical tide (HAT)	1.1m
Mean High Water Springs (MHWS)	0.7m
Mean High Water Neaps (MHWN)	0.4m
Mean Sea Level (MSL)	0.0m
Mean Low Water Neaps (MLWN)	-0.4m
Mean Low Water Springs (MLWS)	-0.7m

While tidal levels in Newcastle are:

Highest astronomical tide (HAT)	1.1m
Mean High Water Springs (MHWS)	0.6m
Mean High Water Neaps (MHWN)	0.4m
Mean Sea Level (MSL)	0.0m
Mean Low Water Neaps (MLWN)	-0.4m
Mean Low Water Springs (MLWS)	-0.6m

Note that MSL has a level of approximately 0.0m AHD.

3.4 Tidal Discharges in the Hunter River Information

Tidal flows in the Hunter River have an influence on the water levels at the river entrance therefore a review of discharges was carried out. The most recent measured flow data was obtained from the Stockton Beach Coastal Processes Study (DHI 2006) where tidal flow currents were measured over a period of 2 weeks at a fixed location and also across a transect in the river mouth. The data collection period for this exercise was planned so that the measurements would capture both the spring and neap tide cycles. Figure 3-6 shows the water levels (m AHD) during the measurement period.

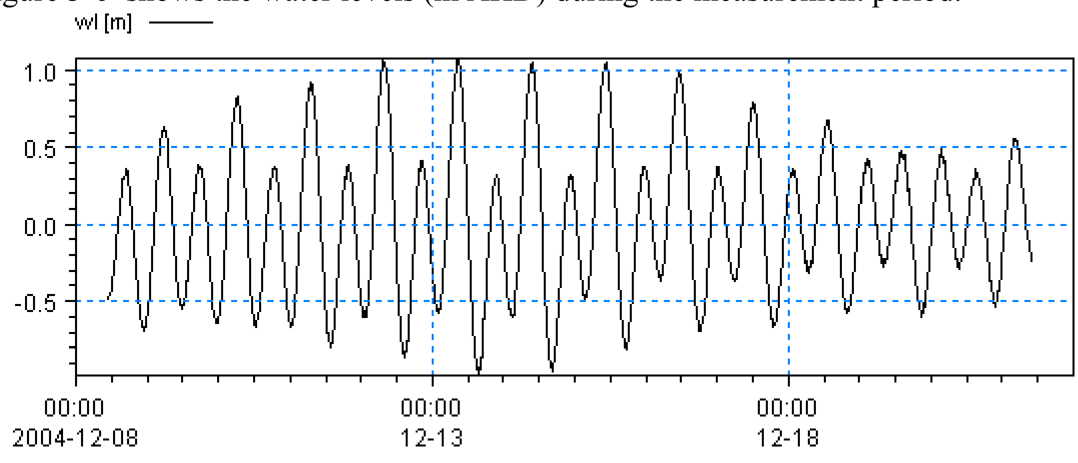

Figure 3-6 Water levels at the Hunter River Entrance during the measurement period.

Figure 3-7 illustrates the location of the bottom mounted ADCP and the two flow transects. Transect 1 wasn't initially defined but was included during the Dec-14 measurements due to large wave action at the river entrance. However as the wave conditions improved the measurements were completed in transect 2 (as originally planned). Transect 2 was also used during the neap measurements on Dec 21, 2004.

Figure 3-7 Location of the proposed ADCP bottom mounted and transects at the river entrance as well as the location of the nearshore measurements carried out by MHL off Stockton Beach.

The bottom mounted ADCP provides a detailed description of the flow velocities and direction at different distances from the seabed. As an example Figure 3-8 shows the measured current speed (middle) and direction (below) at 9.9 metres above the seabed. This figure includes also the measured mean pressure (above) that allows us to relate current speed and direction to water levels. As it can be observed, current speeds exceeding 0.8 m/s were observed during Dec 14 when spring tidal levels occurred however the typical current speed was approximately 0.4 m/s.

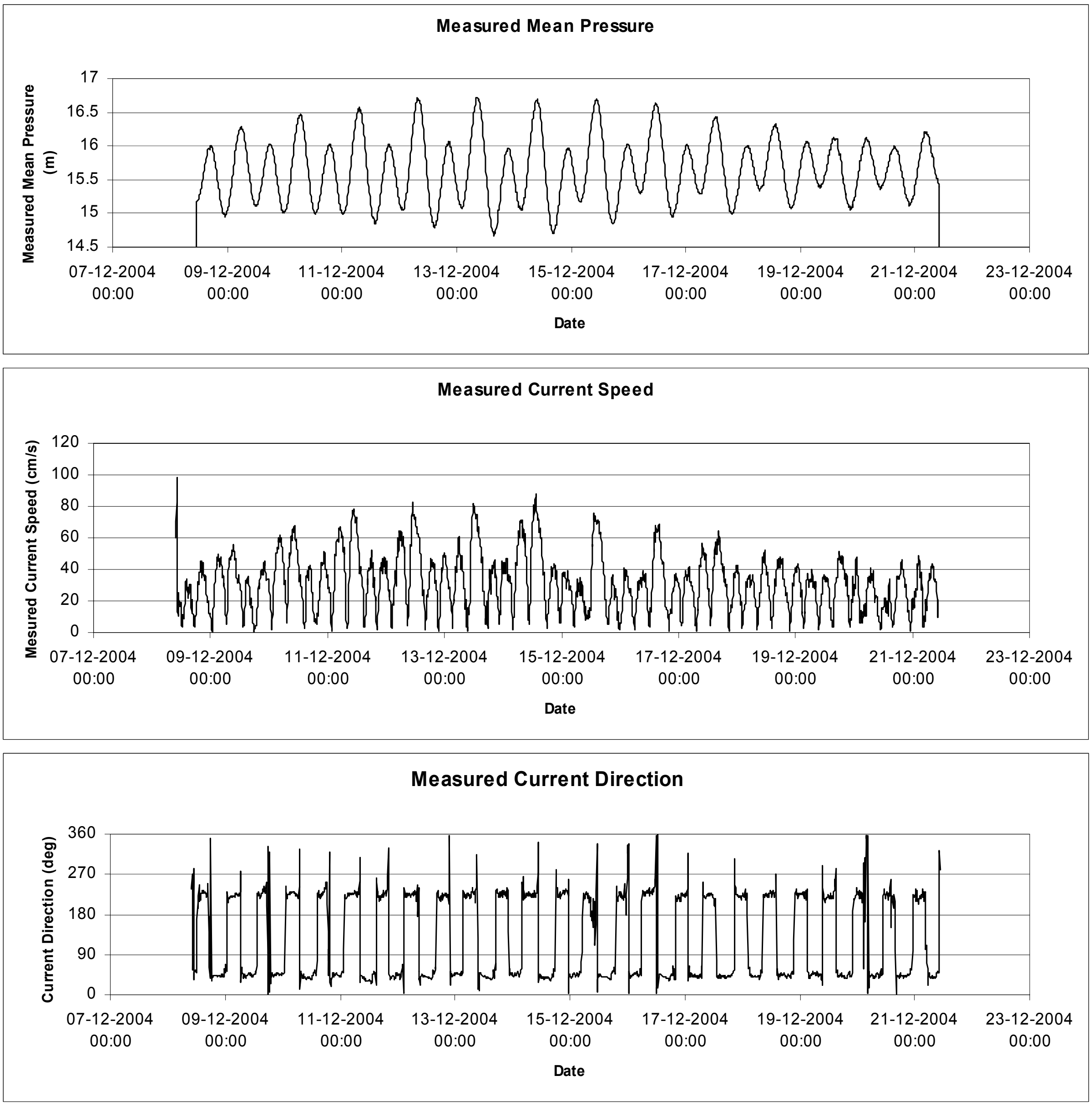

Figure 3-8 Measured mean pressure and measured speed and direction at 9.9 metres from the seabed

During this two week measurement period ADCP transects were carried out during spring and neap tide water levels the following days:

- Spring tide - 14 December 2004;
- Neap tide - 21 December 2004.

The ADCP transects were undertaken in a surveying boat with the ADCP instrument attached. The transects were carried out at approximately 15 minutes intervals and then integrated across the measured cross section to obtain the tidal flow in and out of the river.

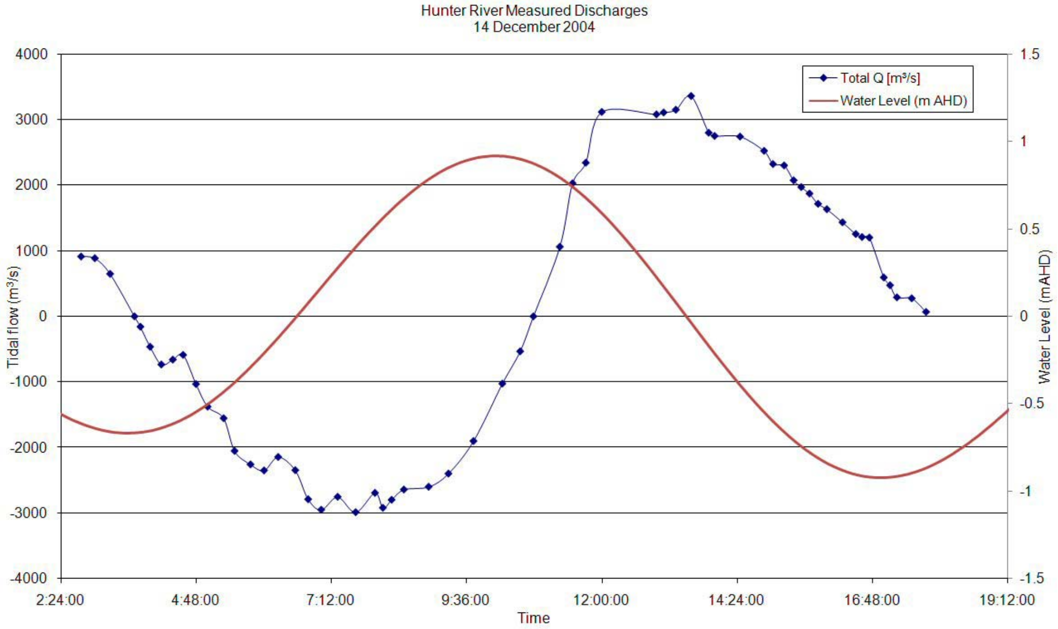

Figure 3-9 Computed discharges (m^3/sec) during spring tidal levels.

The computed discharges at the Hunter River entrance for the spring and neap periods are shown in Figure 3-9 and Figure 3-10. Maximum discharges of 3000 m^3/s were measured during spring period and 1500 m^3/s during neap period. However, it should be noted that the flow and water level are out of phase so that at peak high tide (i.e. high water slack) and low tide (i.e. low water slack) the tidal flows are approximately zero.

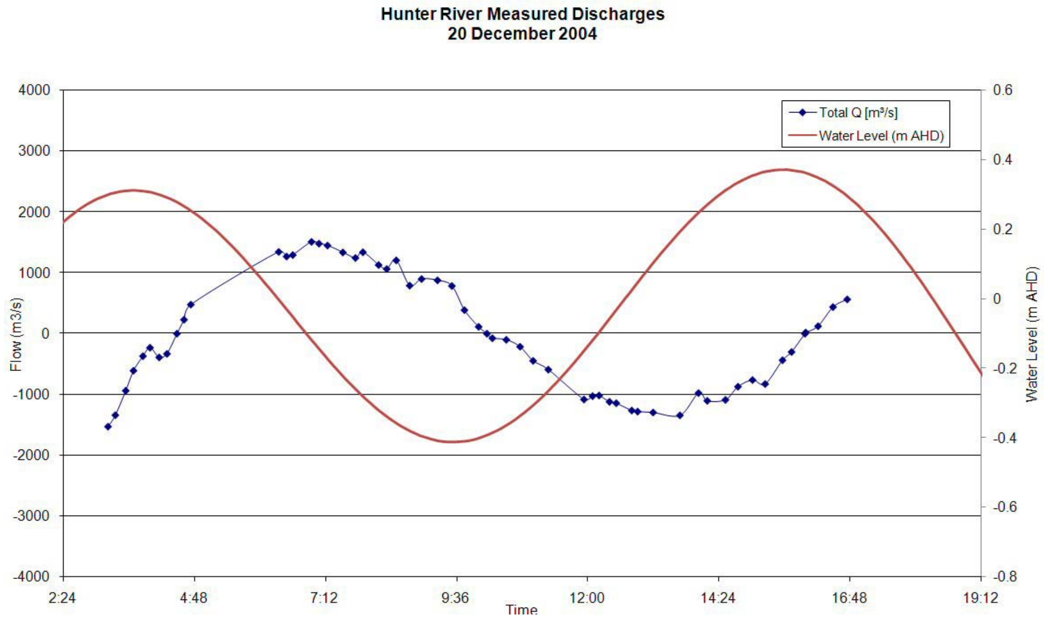

Figure 3-10 Computed discharges during neap tidal levels.

4 EXTREME WAVE MODELLING TO DETERMINE WAVE SET-UP

4.1 Extreme Wave Modelling Introduction

The objective of this sub-activity was to describe the wave conditions in the Newcastle Harbour entrance study area by applying a wave modelling approach and to use the description of the modelled wave climate to determine wave induced set-up. This approach includes the description of various wave phenomena such as: shoaling, refraction, diffraction, bottom roughness and wave breaking among others. The description of all these processes represents the propagation of the offshore wave conditions into the study area. This is a computationally demanding exercise as the study area has to be resolved adequately.

In order to provide an accurate and at the same time a computationally efficient solution DHI has applied a hybrid approach to the analysis. The approach makes use of a regional numerical wave model based on the MIKE 21 Spectral Wave (SW) model for transforming offshore wave conditions to the nearshore zone and the MIKE 21 Parabolic Mild Slope (PMS) model to develop a description of the wave climate in the nearshore zone including inside Newcastle Harbour.

While MIKE 21 SW provides an efficient tool for transforming averaged wave climate conditions from offshore into the nearshore area, it does not include wave diffraction, which is relevant in Newcastle Harbour due to the wave dissipating effect of diffraction by the river entrance breakwaters. For this reason, MIKE 21 PMS was applied to determine the nearshore wave climate. Boundary conditions for the nearshore MIKE 21 PMS model were obtained from the MIKE 21 SW model analysis. This coupled approach made it possible to predict the local wave conditions and radiation stresses in the study area including inside the harbour by using MIKE 21 PMS in a reduced model domain.

The results of the local wave model were subsequently applied as a forcing function in the MIKE 21 Hydrodynamic Model (HD) in order to predict wave induced water level set-up. An overview of the modelling strategy is presented in Figure 4-1.

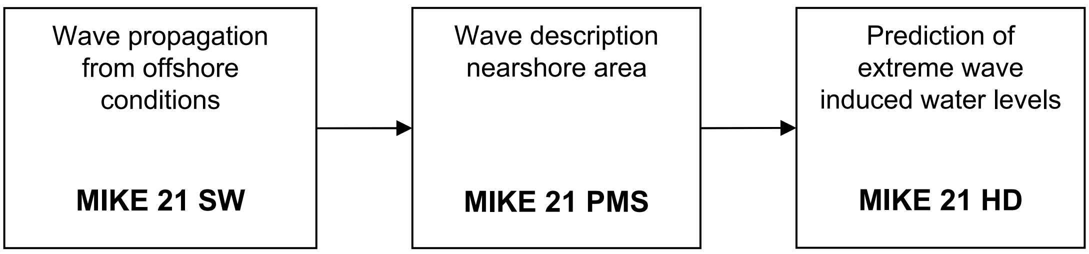

Figure 4-1 Overview of the proposed modelling strategy

MIKE 21 PMS is a wave model based on a parabolic approximation to the mild-slope equation governing the shoaling, refraction, diffraction and forward reflection of linear water waves propagating on a gently sloping bathymetry. The parabolic approximation is obtained by assuming a principal wave direction (x-direction, perpendicular to the coast), neglecting diffraction and backscatter along this direction. An additional feature of MIKE 21 PMS is the ability to simulate directional and frequency spreading of the propagating waves by applying linear superposition. MIKE 21 PMS can be applied to any water depth on a gently sloping bathymetry and it is capable of reproducing phenomena such as shoaling, refraction, dissipation due to bed friction and wave breaking, forward scattering and partial diffraction. Dissipation due to wave breaking is modelled by Battjes and Janssen's approach.

The inputs to this hybrid modelling strategy included:

- Directional offshore wave data at the Sydney buoy;
- Basic model parameters describing the extent of the model area, the grid spacing of the computational model grid, the time step and the duration of the simulation;
- Bathymetric information that covers the study area;
- Information of tidal currents at the harbour entrance; and
- Incident wave conditions at the boundaries of the model area.

The computed wave radiation stresses obtained from the MIKE 21 PMS model were applied into the local MIKE 21 HD model. This model allows the description of the hydrodynamic conditions in the study area based on the definition of the wave forcing mechanism through the model boundary conditions as wave radiation stresses.

4.2 Extreme Regional Wave Modelling – transformation of offshore wave conditions to the nearshore zone

A regional MIKE 21 SW model of the study area was established with the extent presented in Figure 4-2. The wave boundary conditions applied in the model were obtained from the waverider buoy at Sydney moored 12 km east of Curl Curl Beach in approximately 85m water depth to the local model boundaries.

Model results showing an example of the MIKE 21 SW model outputs are presented in Figure 4-2 below (the axes are distances in metres to MGA Zone 56 projection). The results represent the extreme offshore wave conditions of Hs=14.2m, Tp= 15sec and MWD= 105deg (measured clockwise from due north), representing the extreme "burst" wave conditions that would have an impact on Newcastle Harbour.

Note that both MIKE 21 SW and MIKE 21 PMS are static models which spatially transform wave conditions represented by averaged parameters across the model domain. The dynamic process of wave set-up which is influenced by the persistence and duration of a wave condition is addressed by the MIKE 21 hydrodynamic model. A description of the hydrodynamic model processes is provided in Section 4.4.

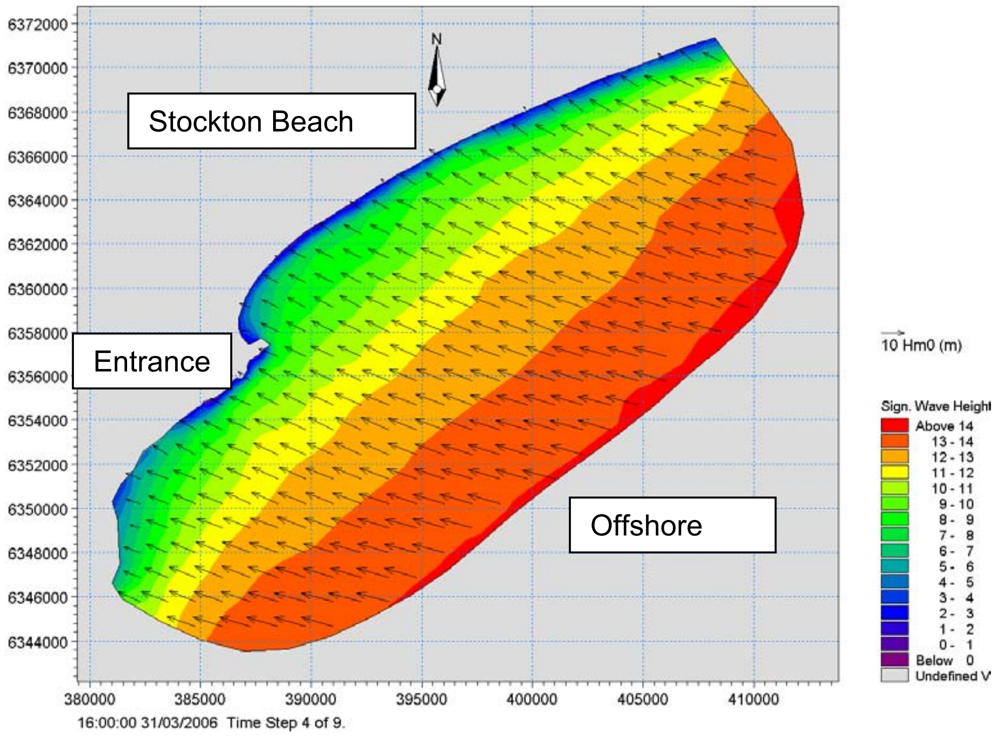

Figure 4-2 Overview of the MIKE 21 SW model wave height predictions.

As limited definitive information of the direction of extreme wave off shore the NSW coastline is available, a detailed analysis of the effect of the offshore wave direction on inshore wave conditions was undertaken. A series of model simulations were undertaken with the adopted significant wave height of Hs= 14.2m and peak wave period Tp= 15sec while varying direction of the offshore waves. The results of the simulation have been extracted just offshore of the river entrance and are presented in Figure 4-3.

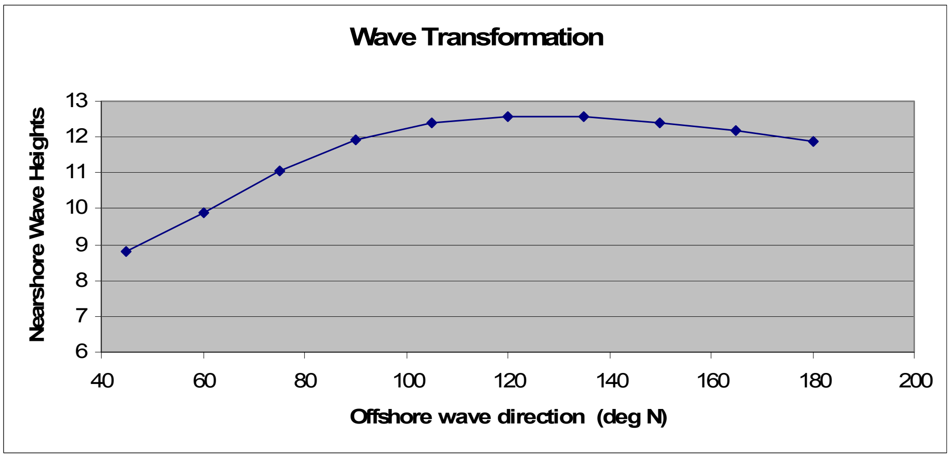

Figure 4-3 Relationship between offshore and nearshore wave condition at the Hunter River Entrance (constant wave height offshore 14.2m, Peak Period 15s and varying mean wave direction)

As it can be observed from Figure 4-3 the largest waves in the nearshore zone occur for offshore waves propagating from 90 to 180 degrees (0 degrees is true North, and 90 degrees is due East and so on). Based on this information the following offshore and nearshore conditions have been applied in the more detailed extreme water level set-up analysis:

Offshore wave conditions:

- Hm0: 14.2m, Tp = 15 sec MWD : 90deg
- Hm0: 14.2m, Tp = 15 sec MWD : 105deg
- Hm0: 14.2m, Tp = 15 sec MWD : 120deg

Nearshore wave model boundary conditions:

- Hm0: 11.9m, Tp = 15 sec MWD : 104deg
- Hm0: 12.4m, Tp = 15 sec MWD : 114deg
- Hm0: 12.6m, Tp = 15 sec MWD : 126deg

4.3 Nearshore Area Extreme Wave Modelling – developing extreme wave climate conditions for the harbour entrance

The prediction of the wave induced elevated water levels at the Hunter River Entrance requires the prediction of the wave conditions and the wave radiation stresses in the nearshore area including the area inside the harbour.

In order to predict the wave conditions in the vicinity of the Hunter River Entrance, a detailed MIKE 21 PMS model of this study area was established. The extent of the nearshore model is presented in Figure 4-4. The wave model has a detailed resolution to describe the wave processes and has been extended to a suitable distance remote from the Hunter River entrance to avoid boundary effects influencing results in area of interest.

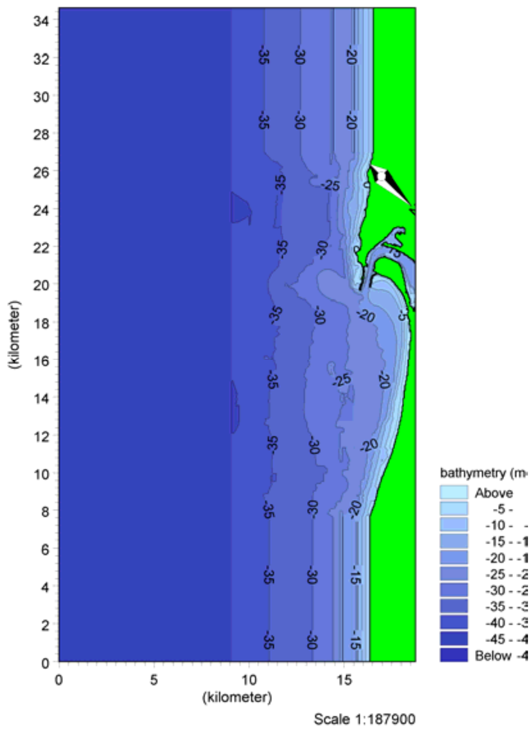

Figure 4-4 Overview of the model bathymetry applied for the nearshore wave modelling.

The three proposed wave cases have been modelled to produce wave conditions and wave radiation stresses in the study area. Wave radiation stresses provide the forcing mechanism that induces the wave induced water level set-up.

As an example of the application of this model, the figure below shows the predicted wave field for Case 2, with significant wave heights of 14.2m, Peak Period of 15 sec and mean wave direction of 114 deg. The length and direction of the arrows show the wave height and wave direction respectively and the colour gradation provide information on wave heights.

These simulation results describe the wave conditions in the harbour and nearby areas. The simulations have been performed for irregular waves synthesised on the basis of the pre-defined offshore wave spectra. A directional spreading coefficient n=12 has been included in the simulations.

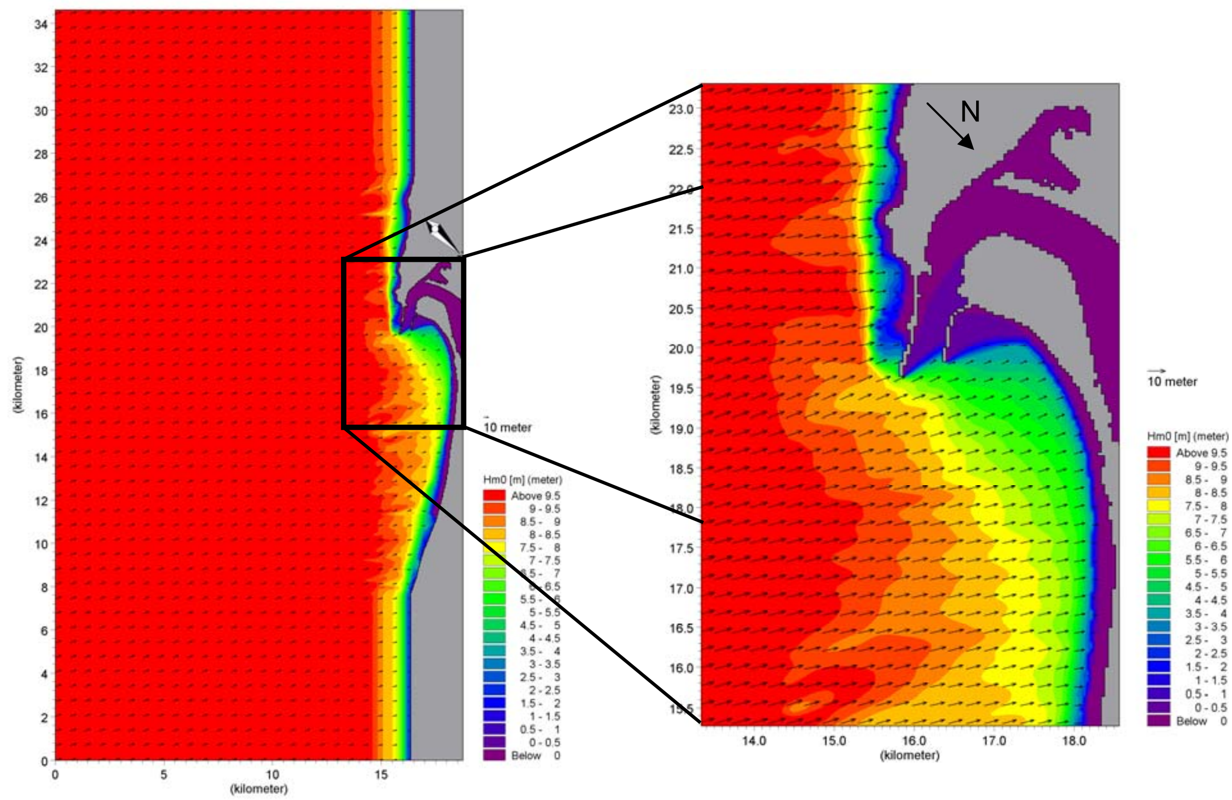

Figure 4-5 Example of the wave predictions in the Study Area.

4.4 Extreme Wave Set-up Modelling Results

When waves propagate towards the coast they transform, influenced by the bathymetric conditions of the area. As the waves approach shallow areas they tend to shoal and become steeper and eventually break. During the process of breaking the waves tend to induce a variation in the mean water level. This is usually defined as a wave set-up, which is basically a rise in the average water level above the still water-level elevation of the ocean.

In order to determine the effect of wave induced setup on the extreme water levels at the Hunter River Entrance, a two dimensional hydrodynamic model of the area has been established. This model includes, as model boundaries, wave radiation stresses induced by the wave breaking, which were predicted in the wave model, described in the previous section.

The simulations were carried out for a constant regional water level equal to the mean sea level.

A total of 3 scenarios covering the three offshore wave conditions all simulated with a constant water level (0m AHD) were analysed.

Table 4-1 Overview of modelling scenarios for wave-set-up analysis

Case	Hm0 (m)	Tp (sec)	MWD (deg)	River Discharge (m3/s)
1	11.9	15	104	0
2	12.4	15	114	0
3	12.6	15	126	0

Each model simulation was run from a ‘calm’ standing initial condition (horizontal initial water surface in the model, no waves) of mean sea level (0m AHD) and run until steady state conditions were reached for each of the listed flow and wave boundary combinations.

The results of the simulations provide a description of the wave induced setup in the study area. Maximum water levels have been presented for the harbour entrance to provide an overview of the maximum water levels expected for each offshore wave condition analysed. The results of the simulations are presented in Figure 4-6, Figure 4-7 and Figure 4-8.

The results of the simulations show that Cases 2 and 3 produce the largest increase of the water levels at the river mouth (as measured at the location shown in Figure 1-1). This is expected as the incoming waves are able to propagate into the Hunter River entrance without significant dissipation. In these cases water level set-up of up to 0.1m above still water level is predicted. It should be noted that this case is perhaps the most relevant to an extreme water level analysis as it represents conditions at high tide ‘slack water’.

The predicted values at the river entrance are well below those observed on the beaches, but this is expected due to the larger water depths in the river entrance which reduce the possibility of waves breaking.

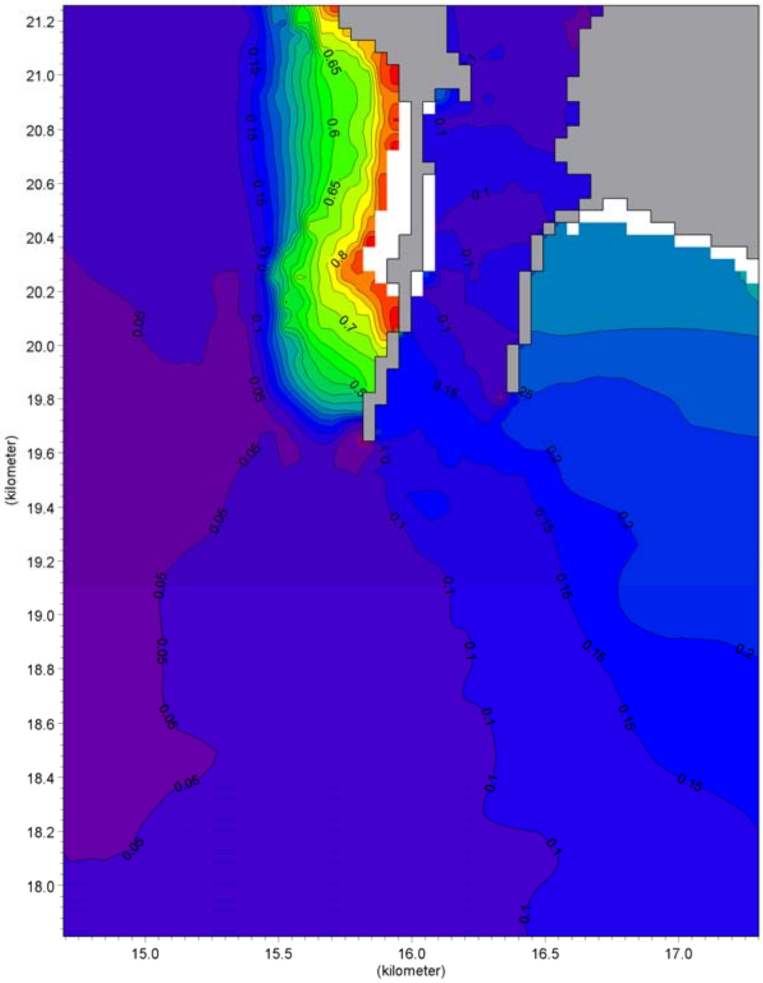

Figure 4-6 Extreme Wave Modelled maximum surface elevation predictions for Case 1

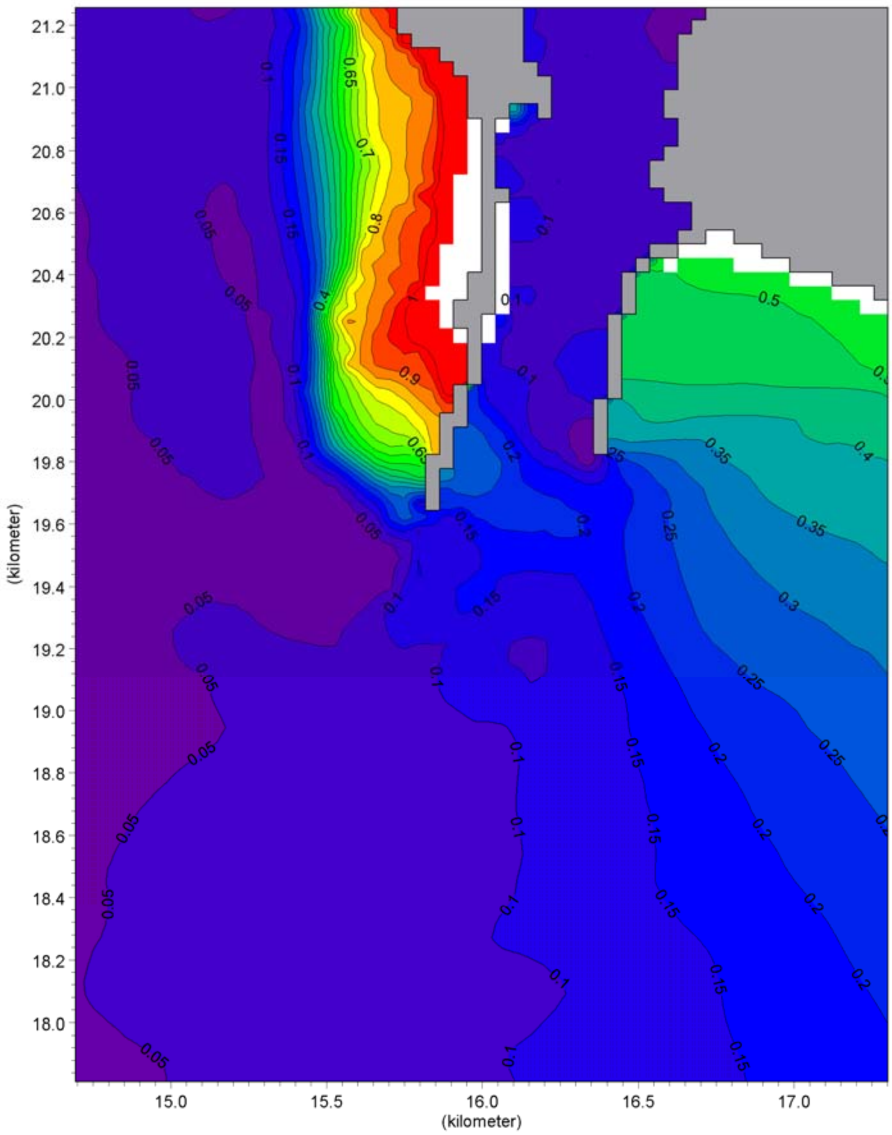

Figure 4-7 Extreme wave modelled maximum surface elevation predictions for Case 2

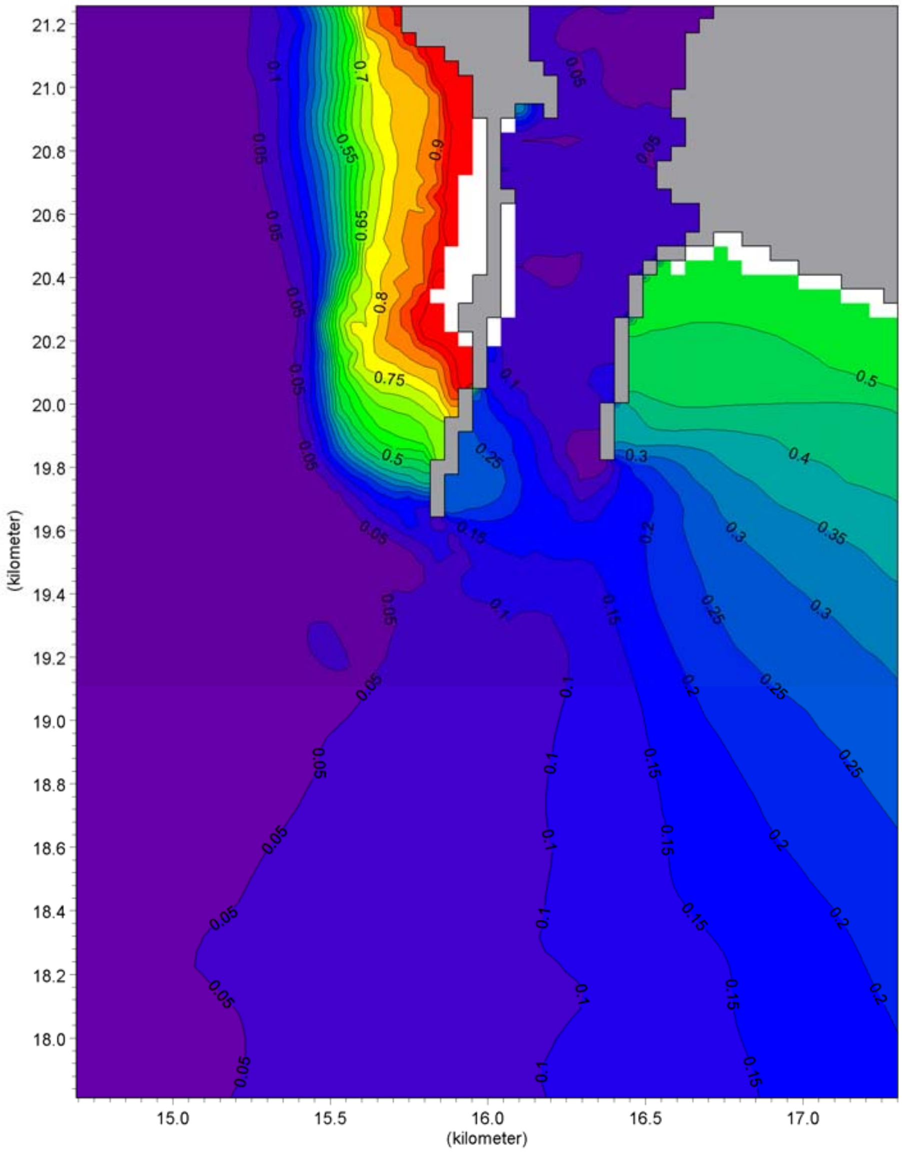

Figure 4-8 Extreme wave maximum surface elevation predictions for Case 3

Table 4-2 presents a summary of wave set-up values for the representative reporting location shown in Figure 1-1.

Table 4-2 Summary of Modelled Extreme Wave Set-up

Case	Nearshore Hm0 (m)	Nearshore Tp (sec)	Nearshore MWD (deg)	Wave Set-up (m)*
1	11.9	15	104	0.10
2	12.4	15	114	0.10
3	12.6	15	126	0.10

*Typical Location (White dot on Fig 1-1)

The analysis described above has been undertaken on the basis of adopting an instantaneous or “burst” peak wave height. For such short duration events, the penetration of the associated wave set-up would be restricted primarily to the immediate Newcastle Harbour entrance area only.

Analysis undertaken for this study using the hybrid approach described in Section 4.1 as well as an analysis undertaken for the Newcastle Ports Corporation (DHI 2006) using a more comprehensive, but computationally intensive Boussinesq wave modelling approach (see Figure 4-10) confirms that elevated ocean wave set-up is limited for instantaneous waves to an area local to the Hunter River entrance.

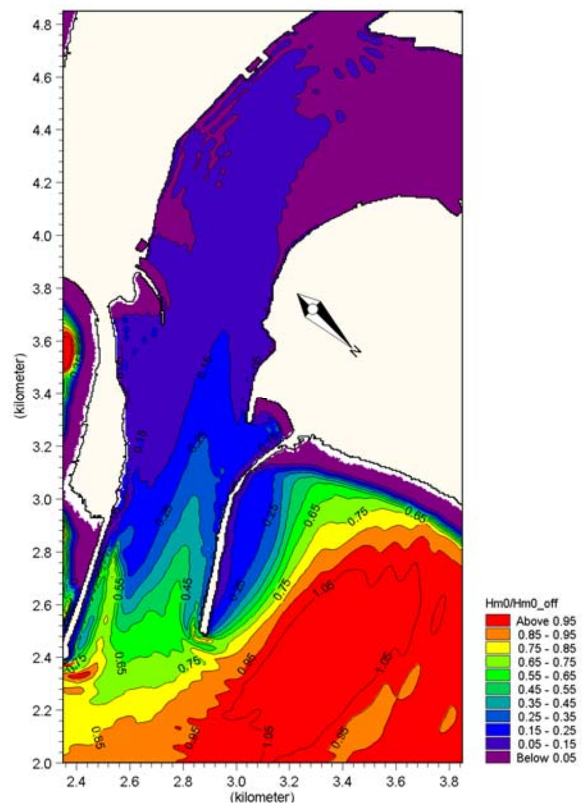

Figure 4-9 Relative wave heights inshore to offshore for wave direction 80 degN (DHI 2006).

For areas of the estuary that are beyond the immediate "wave influence" zone of Newcastle Harbour, wave set-up of water levels would be attributable to longer duration offshore wave conditions (i.e. durations greater than 6-12 hours). For these conditions, the offshore wave height would be less than the instantaneous wave heights used in the above analysis. Wave set-up for the remainder of the estuary should be obtained through application of the hydrodynamic flood model, adopting a slightly elevated tailwater (ocean) level. It has been determined that a offshore wave height of Hs=14.2m generates a wave set-up of 0.1m, so it can be anticipated that a lesser offshore wave height (i.e. approximately Hs=10m, see Section 3.2) would therefore produce a set-up of between 0.05 and 0.1m. Thus, within numerical analyses, offshore boundary conditions should be increased by up to 0.1m to account for wave set-up.

5 RECOMMENDED VALUES FOR EXTREME ELEVATED OCEAN LEVELS

Based on information collected from the literature review and the modelled wave scenarios it is possible to determine estimates of the elevated ocean level components that can contribute to extreme ocean water levels in the vicinity of the Hunter River entrance. Extreme ocean levels occur due to a range of phenomena including tidal variations, the effect of barometric and wind setup (usually defined as storm surge) and wave setup (See Section 2).

5.1 Astronomical tides component

Typically, tides in Newcastle have amplitude of between 1m and 1.5m during neap and spring conditions respectively. An analysis of tidal levels to establish extreme astronomical tide heights has been carried out and an exceedance water level curve has been produced. The analysis was carried out based purely on tidal predictions which excludes tidal anomalies. Based on this information, it has been determined that the highest astronomical tide (HAT) has a level of 1.1m AHD, 2.1m referred to local datum, and that tides in the order of 1.05m AHD occur several times each year.

5.2 Extreme Storm Surge (Barometric and Wind Effects) component

5.2.1 Adopted Extreme Storm Surge Methodology

Barometric setup is produced by the forcing induced by a low atmospheric pressure field. It is commonly assumed that a 1kPa drop in pressure produces a super-elevation of the ocean surface of 1cm. This is often accompanied by wind setup occurring from the same storm event caused by strong onshore winds forcing an elevation of the water surface against the coastline.

It was concluded that the only feasible methodology for this study was an historic and literature search approach with a focus on the study area as it was considered that recorded extreme storm surge meteorological and water level measurements from overseas locations may over-estimate what is physically possible on the NSW coastline. It is theoretically possible to attempt computer numeric simulation of extreme storm surge conditions, and while this may be attempted by further research, it was beyond the practical scope of this commission.

5.2.2 Historic Extreme Storm Surge - Information and Analysis

Since it is the case that inverse barometric effects and wind set-up are often caused by the same storm, it is difficult to separate these two effects as component phenomena in an extreme elevated water level analysis. Based on information provided by the Bureau of Meteorology (Personal communication Jeff Callaghan BOM) the lowest pressure measured in the Sydney area since 1951 was observed in November 1951, at a minimum of 985.7 hPa. Estimates provided by the NSW Government's Coastline Management Manual (1990), indicate that inverse barometric effects in the NSW region are up to 0.4m, being slightly larger to that estimated from the low pressure observations in the Sydney area (1013hPa (average pressure) -985hPa/1hPa/cm: 0.28m). The same reference estimates that maximum water elevation due to wind set-up can be up to 0.2m. Geary and Griffin (NSW PWD, circa 1980) considered that a wind set-up of 0.3m and an inverse barometric pressure set-up of 0.5m maximum, totalling 0.8m max for storm surge were appropriate for NSW to represent extreme conditions.

On the basis of this sourced information a storm surge in the extreme range of 0.8m is recommended.

5.3 Extreme Wave Set-up Component

A modelling analysis has been undertaken to determine an appropriate range for wave set-up. The modelling analysis as outlined in Section 4 used a hybrid modelling approach to transform extreme offshore wave conditions to the nearshore and then to estimate wave set-up in the Hunter River entrance based on the nearshore wave climate estimates.

The modelling analysis showed that an instantaneous wave ("burst" conditions) would generate a wave set-up within the Newcastle Harbour entrance area of 0.1m. Locally, within the harbour area, water levels may also be subject to standing wave conditions during ebbing or flooding tides. These local resonance conditions cannot be predicted using standard hydrodynamic or wave simulation software.

For the remainder of the estuary, longer duration wave conditions would be required to generate wave set-up. From interpretation of the instantaneous wave modelling analysis, an extreme wave set-up across the remainder of the estuary of 0.05 to 0.1m can be expected.

5.4 Other Extreme Water Level Set-up Components

There are other offshore phenomena that may cause an elevated ocean level on the NSW coastline. These phenomena can, however, be considered as independent from an extreme storm offshore of the NSW coast which causes storm surge and wave set-up. These phenomena include:

- steric effects (variations in ocean salinity and temperature); general estimate of around +/- 0.1m;
- climatic influenced phenomena such as the El Nino Southern Oscillation and the influence of strong currents such as the East Australian Current (EAC) which moves south along the eastern coast of Australia and can cause eddy formations. An eddy moving in a clockwise direction causes a depression in the sea surface while an eddy moving in an anticlockwise direction can cause an elevation, however it is not clear yet how these eddies interact in the nearshore areas. ENSO results from interactions between the atmosphere and major ocean currents over the Pacific Ocean and appears to occur about every three to seven years (NSW government, 1990); general estimate of around +/- 0.1m; and
- coastally trapped waves which are produced by meteorological disturbances are characterised by a sharp pressure gradient, generating a long low wave with a period of up to 10 days and a height of 0.2 to 0.3m (NSW Government, 1990). As the wave travels anticlockwise along the coast it becomes trapped and the shelf acts to guide the wave as it modifies coastal water levels. A storm in Syd-

ney can cause a coastally trapped wave to travel north to Queensland, while a wave generated in Darwin can be 0.4m height and diminish as it travels around the coast as far as Adelaide (Griffin, pers. com., 2007). General estimate for coastally trapped waves of around 0.3m.

5.4.1 Climate change effects

Sea-level rise is one of the projected outcomes of climate change documented in the three successive reports over the last decade by the Intergovernmental Panel on Climate Change (IPCC). The IPCC's main objective was to assess scientific, technical and socio-economic information relevant to the understanding of human-induced climate change, potential impacts of climate change and options for mitigation and adaptation.

The NSW Department of Environment and Climate Change has reviewed the IPCC (2007) reports and produced a floodplain risk management guideline document "DECC FRM Guideline: Practical Consideration of Climate Change" (DECC 2007). This document identifies that IPCC predicted sea level rise trends on the NSW coastline may fall in the range of 0.18m to 0.91m by 2090- 2100. This range of values for sea level rise has been adopted for this report.

5.5 Summary of Recommended Extreme Ocean Level Elevation Components

The results in Table 5-1 are indicative of the anticipated range of each oceanographic and meteorological phenomena considered. Each phenomenon has been quantified by a water level increase component range applicable at the extreme end of the risk probability scale.

An example of how the values in this table might be applied is provided in Section 6.

Table 5-1 Summary of Extreme Elevated Ocean Level Components

Conditions	Phenomenon	Water Levels
Extreme Storm	Storm surge and wave set-up	0.8m +0.1m 0.9m
Coincident with one or more independent phenomena	Astronomical tide Steric effects Climate influences Coastal trapped waves	up to 1.1m AHD* 0.1m 0.1m 0.3m
Plus climate change effects	Sea level rise at 2100	0.18 -0.91m**

* high range is HAT
** dependent on planning horizon and climate change scenario

5.5.1 Application of Extreme Ocean Levels

There are three components of the extreme ocean levels. The first component is associated with an extreme storm, causing wind, wave and barometric effects. This will generate both storm surge and wave set-up within the Hunter Estuary. The duration of an extreme storm is likely to be in excess of 48 hours, with storm surge components essentially increasing and then decreasing as the storm cell moves past the local vicinity. The actual shape of the hydrograph can be highly variable. Larger storms are likely to be attributed to larger duration events, as barometric influences can draw-up water from further afield.

The second component relates to phenomena occurring independent of the extreme storm condition. Highest Astronomical Tide (HAT) (a level of 1.1m AHD in Newcastle Harbour) occurs once every 17.6 years, however, king tide conditions with levels greater than 1.05m AHD occur several times per year. Based on the Mean High Water Springs level, there is a 1 in 4 chance in that the astronomical tide on any day will exceed 0.6m AHD in Newcastle Harbour. Other effects, including steric effects, climatic influences and coastal trapped waves, are unpredictable phenomena unrelated to a specific storm event. Inclusion of these within any analysis should reflect the extreme joint probability of occurrence of these phenomena and any coinciding storm.

The third component relates to future climate change and sea level rise in particular. A range of projected values for sea level rise has been provided. The applicability of sea level rise values with any future analysis will depend on the time frame and planning context of analysis and the degree of risk adversity required.

6 EXAMPLE APPLICATION OF AN EXTREME ELEVATED OCEAN LEVEL FOR FLOODPLAIN PLANNING

The following hypothetical floodplain management scenario is provided as an example application of the extreme elevated ocean level data and analysis presented in this report.

"A site at Hexham has been identified in a preliminary list of locations for a new regional hospital to be developed. Identify any flooding constraints due to storm surge."

As key regional infrastructure, the hospital site and its road access are required to be flood free for the full range of possible floods including an extreme flood storm surge. Review of the extreme ocean level components listed in Table 5-1 provided the following elevated ocean level components appropriate for this scenario:

Table 6-1 Summary of Scenario Specific Elevated Ocean Levels

Elevated Ocean Level Component	Value	Discussion
Tide	1.05m AHD	Coincidence of extreme storm and HAT considered too unlikely
Storm Surge	0.8m	Extreme storm surge
Wave Set-up	0.1m	Extreme wave conditions for a duration of > 6-12 hours
Other effects	0.1m	Some possibility of additional coincident phenomena e.g. ENSO or steric or coastal trapped waves
Maximum elevated ocean level	**2.05m AHD**	

In order to determine the appropriate flood level at the Hexham site, the additional components were applied superimposed on a representative tide (max 1.05m AHD) time series as the ocean boundary for the Lower Hunter River flood model (DHI, 2007). The ocean boundary time series was generated using the approach recommended in the NSW Government "Floodplain Risk Management Guideline No. 5: Ocean Boundary Conditions (Draft)", (DIPNR 2005). Generation of the ocean boundary involves superimposing a tidal time series with the calculated storm surge anomaly to generate a storm tide as illustrated in Figure 6-1.

The duration of the storm adopted was approximately 170 hours. For the purposes of this example, the 'other effects' were simply added to the same storm hydrograph, with the peak water level increase coinciding with peak astronomical tide level.

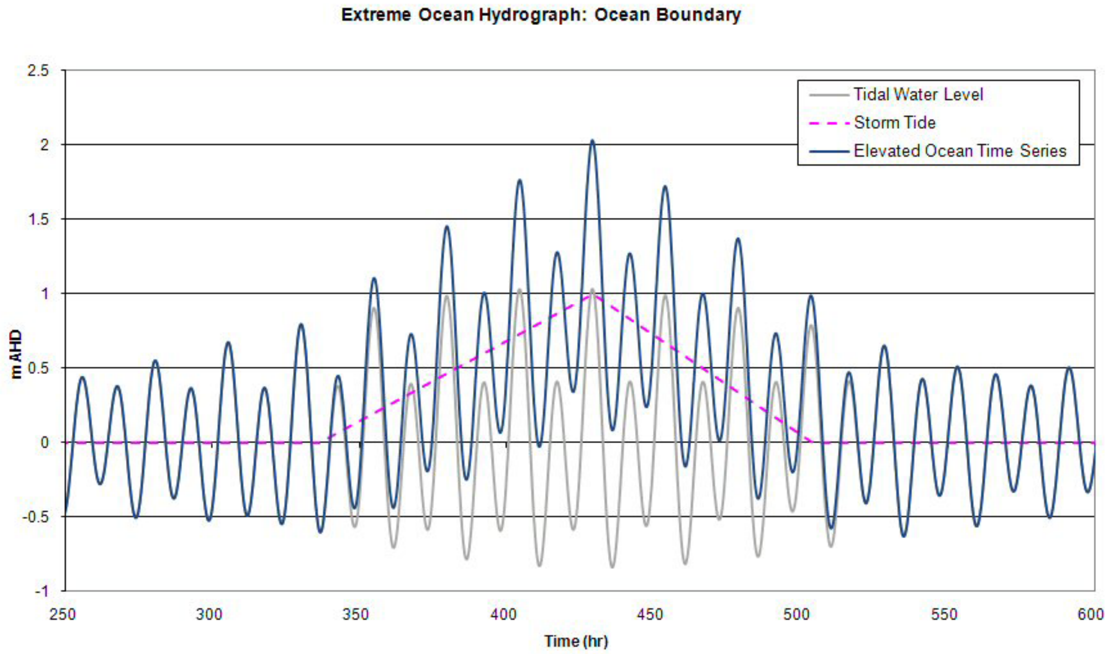

Figure 6-1 Ocean Boundary - Lower Hunter River Flood Model

The derived ocean storm tide was applied to the Lower Hunter River model and from the model results presented in Figure 6-2 it was determined that the peak storm tide level at the Hexham site was 1.9m AHD as compared to the ocean storm tide level of 2.05m AHD. The model results indicated that the storm tide peaked at Hexham approximately 2 hours after the corresponding ocean level maximum. Figure 6-3 shows the propagation of the peak storm tide level compared to the peak tide level without anomaly as a profile along the north arm of the Hunter River from the ocean to Green Rocks. Figure 6-4 presents the same tide profiles compared to the Probable Maximum Flood profile from the Lower Hunter River flood study (DHI 2007).

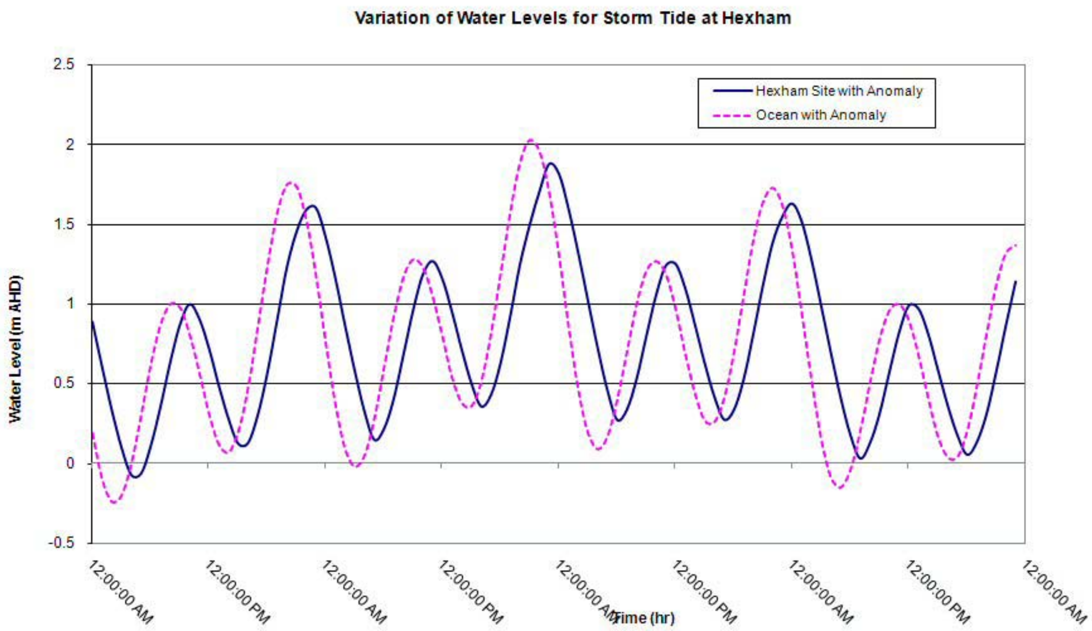

Figure 6-2 Peak Storm Tide Level - Lower Hunter River Flood Model at Hexham

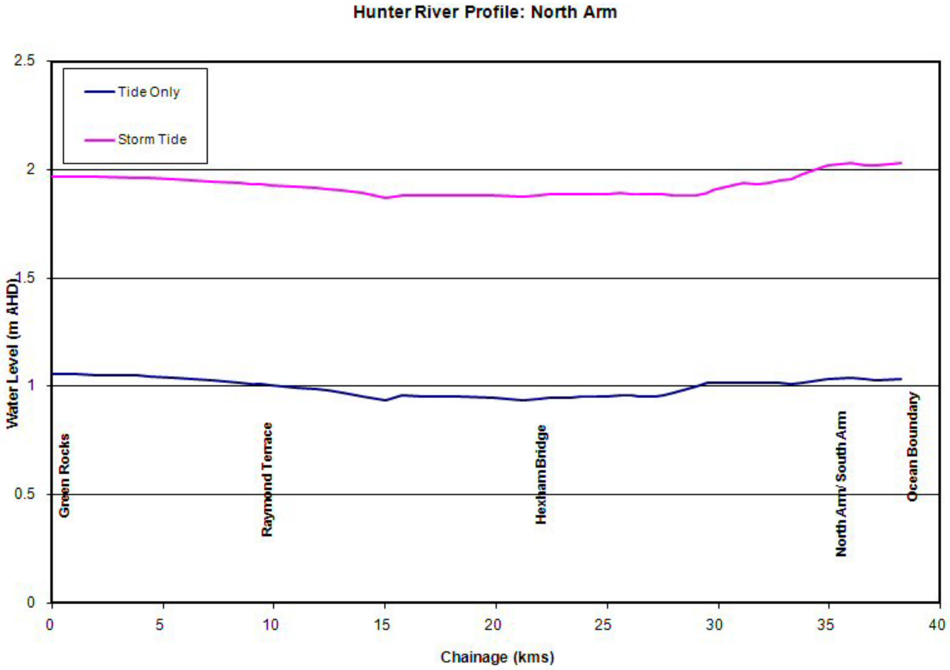

Figure 6-3 Peak Storm Tide Level vs. Peak Tide Level - Lower Hunter River longitudinal profile

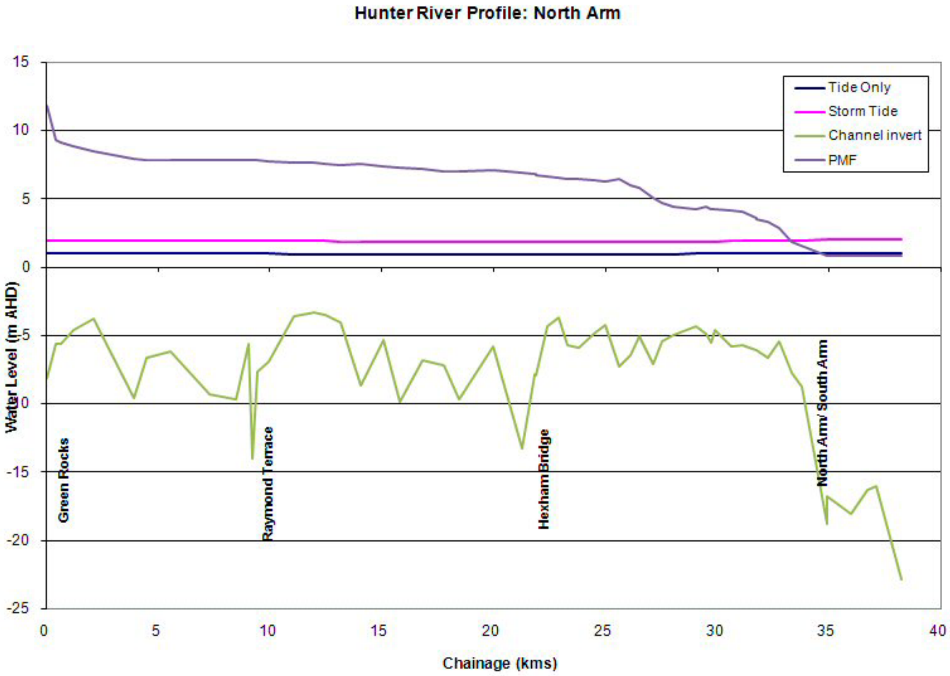

Figure 6-4 Longitudinal Profile – Hunter River North Arm – Storm Tide vs. PMF

7 REFERENCES

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8 ACKNOWLEDGEMENTS

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DHI Software Descriptions

MIKE 21 SW and PMS