Wave Climate Report

Prepared for Gladesville Bridge Marina

October 2019

MetOcean SOLUTIONS

Document History

Versions

Version	Revision Date	Summary	Reviewed by
0.1	06/06/2019	Draft for internal review	Thiebaut
0.2	27/06/2019	Draft for Internal review	Berthot
0.3	10/07/2019	Draft for Client review	Berthot
0.4	02/08/2019	Draft for Client review	Berthot
0.5	28/08/2019	Draft for Internal review	Cussioli/Berthot
0.6	02/09/2019	Draft for Client review	Berthot
0.7	17/10/2019	Draft for Client review	Berthot
1.0	17/10/2019	Final Report	Berthot

Distribution

Version	Date	Distribution
1.0	17/10/2019	Gladesville Bridge Marina

Document ID: 0456

MetOcean Solutions is a Division of Meteorological Services of New Zealand Ltd, MetraWeather (Australia) Pty Ltd [ACN 126 850 904], MetraWeather (UK) Ltd [No. 04833498] and MetraWeather (Thailand) Ltd [No. 0105558115059] are wholly-owned subsidiaries of Meteorological Service of New Zealand Ltd (MetService).

reserves all legal rights and remedies in relation to any infringement of its rights in respect of this report.

Contents

List of Figures

List of Tables

1.Introduction

Gladesville Bridge Marina (GBM) is proposing to improve its marina to meet the growing needs of Sydney's boating community. The marina currently has permission for 99 boats. The proposed changes would result in an increase to a total of 130 boat and storage spaces as follows:

- Increase storage from 50 to 115 boats as marina floating berths
- Maintain 15 commercial mooring spaces
- Increase overall storage spaces by 31

Some of the key features of the proposed improvements include:

- Realigning the structure to reflect earlier sight lines of the marina, and maximise view corridors
- Increasing the total capacity and berth spaces at the marina to meet demand for differing boat sizes
- Removing the slipway and cradles
- Improving amenity

Following the reception of the Secretary's Environmental Assessment Requirements (SEARs), Gladesville Bridge Marina is now preparing an Environmental Impact Statement (EIS) for the proposed development.

As part of the EIS preparation Gladesville Bridge Marina has commissioned MetOcean Solutions (MOS), division of the Meteorological Service of New Zealand (MetService), to undertake a wave climate study, a review of potential climate change impact and flushing conditions for the proposed alterations and additions to the Gladesville Bridge Marina.

A review of the Parramatta River hydrodynamics is provided in Section 2. The marina hydrodynamic circulation and flushing is discussed in Section 3. The metocean study data review and modelling methodology is described in Section 4. Results for the wind and wave conditions are provided in Section 5 and the references cited are listed in the final Section 6.

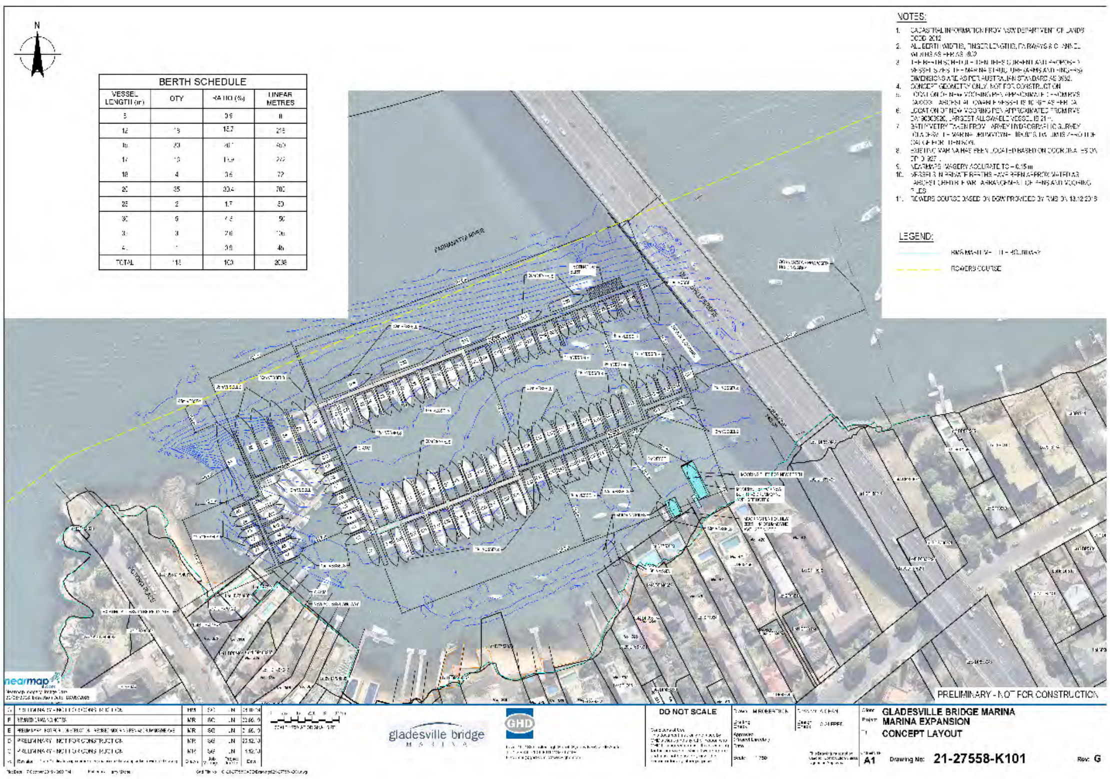

Figure 1.1 Gladesville Bridge Marina locations – Proposed alterations and additions (Aerial Photo Courtesy A. Berthot – Marina Concept Layout GHD)

2. Parramatta River Hydrodynamics and Climate Change

A review of existing literature and report for Sydney Harbour and the Parramatta River estuary was undertaken to identify potential impact of Climate change on local metocean conditions.

The Parramatta River Estuary Coastal Zone Management Plan (CZMP) was finalised in 2013 and adopted by all eight councils along the Parramatta River Estuary. The plan provides an integrated approach to managing the estuary and catchment amongst the many landholders involved.

As part of the CZMP, a Parramatta River Estuary Data Compilation and Review study was undertaken (Parramatta City Council, DECC & Sydney Metro CMA, Cardno 2013) This data review document provides a range of supporting data and references which are of interest for proposed GBM development.

Review of Appendix F - Marine Safety and Navigation Report which refers to regulatory provisions and environmental conditions which will impact clients of the marina and boaters operating in the river, was also undertaken.

2.1 Climate Change impacts:

A summary of the key potential implication of climate change on the Parramatta River, as identified in Cardno (2008, 2013) and AECOM (2010), are presented below:

- Sea level rise (DECC, 2007)
- Increase in intensity of regular and rare catchment flood events (DECC, 2007)
- Increase in the number of ocean wave storm events (IPCC, 2007)
- Increase in oceanic inundation associated with ocean wave events (Ransinghe et al, 2007)
- decreases in annual average rainfall (CSIRO/BoM/AGO, 2007, 2007)
- Increases in temperature and solar radiation (CSIRO/BoM/AGO, 2007)
- Increase in sea surface temperature (CSIRO/BoM/AGO, 2007)

• Increases in evapotranspiration (CSIRO/BoM/AGO, 2007), and

• Increases in wind speeds (CSIRO/BoM/AGO, 2007).

2.1.1 Metocean impacts:

Details on the potential impact of climate change on the local metocean conditions which may affect the marina site are provided below. Climate Change impacts related to water quality, marine ecology or coastal erosion are not part of this study scope however they are listed here as they are related to potential change in meteorological conditions (e.g. rainfall, sea level rise…). It also noted that the design life of the proposed marina is below the 50 year horizon where some of these impacts may become more significant.

Increased water levels:

Sea Level Rise would lead to higher water levels and may also affect the tidal prism (i.e. the amount of water that flows into and out of the harbour). The higher water level may in turn lead to slightly higher wave height in some part of the harbour due to the increased depth and reduced seabed friction. Assessment of the impact of increased water level on wave is presented in Section 5.3.2, Near the marina it is not anticipated that the proposed alterations and additions will increase the potential impact of increase water levels.

Changes in East Coast Lows (ECLs) activity:

Climate modelling projects a decrease in the number of small to moderate ECLs in the cool season with little change in these storms during the warm season. However extreme ECLs in the warmer months may increase in number but extreme ECLs in cool seasons may not change (https://climatechange.environment.nsw.gov.au/Impacts-of-climate-change/East-Coast-Lows). Projected changes in ECLs into the future are smaller than the natural variability observed in ECLs from the historical record. Near the Gladesville Bridge Marina site, the effect of the change in ECLs patterns may include increased storm surge level, extreme wind and waves and associated rainfall. The proposed alterations and additions are not expected to increase the potential impact on the existing marina.

Coastal erosion:

Increased water levels could contribute to the erosion of unconsolidated shorelines. Where there is sufficient fetch, changes in wind patterns could result in increased erosion of affected shorelines by wind waves. The proposed alterations and additions are not expected to exacerbate coastal erosion as they are likely to offer an increase sheltering for local waves and potentially reduce the effect of local wave on the shoreline.

Water quality impacts / Estuarine Ecology:

Extreme weather events and change in rainfall patterns, in particular more frequent flood and drought periods, may impact on catchment processes and potentially lead to a wider range of water quality conditions to occur in the estuary (Parramatta River Estuary CZMP Cardno 2013).

The impacts of climate change on estuarine ecology will be complex and are difficult to predict. Changes in water level may impact intertidal habitats, such as mudflats and rock platforms, which have already been significantly reduced in extent. A rise in mean sea level would also result in a gradual shift in the locations where seagrasses could survive. Water quality and estuarine ecology assessment is not part of this study scope and is anticipated to be addressed in the Appendix J - Marine Ecology Study.

2.1.2 Extreme Water Levels:

Current guidelines for design ocean still water level along the Newcastle-Sydney-Wollongong area are available from the Office of Environment and Heritage (DECC 2010). Table 2.1 provides an estimate of design ocean still-water levels at Fort Denison for varying average recurrence interval (ARI) events in 2050 and 2100 that incorporate provision for sea level rise.

These levels are based on the analysis of water level recorded at Fort Denison which are considered applicable for the Gladesville Bridge Marina area. due to the proximity of the two sites. t

Design still-water levels for 2050 and 2100 incorporate planning benchmark allowances for sea level rise with a reduction of 60 millimetres to accommodate the estimated amount of global average sea level rise that has occurred between 1990 and present (DECC 2010). From satellite altimetry, this is estimated to be 3 millimetres/year (CSIRO, 2009).

Table 2.1 Design ocean still water levels at Fort Denison for 2010 and predicted levels for 2050 and 2100 incorporating projected sea level rise.

Average Recurrence Interval (Years)	2010 Design still water levels (m AHD)	2050 Design still water levels (m AHD)	2100 Design still water levels (m AHD)
1	1.24	1.58	2.08
10	1.35	1.69	2.19
50	1.41	1.75	2.25
100	1.44	1.78	2.28

3. Marina Hydrodynamic Circulation and Flushing

3.1 Existing Hydrodynamics near the Marina

Currents within the Parramatta River Estuary are caused by a range of processes including :

- Astronomical Tides
- Winds
- River Discharges
- Other water level variations from the Tasman Sea (e.g. Coastal Trapped Waves, Tsunamis…)
- Nearshore Wave Processes
- Density Flows

The Parramatta River Estuary is generally well mixed and oceanic during dry or `base-flow' conditions. During periods of high precipitation, freshwater inflow is rapid and a buoyant fresh layer forms on the surface of the waterbody that can be up to two metres thick (Cardno 2008, SIMS 2014, Xiao 2019).

Wind forcing is applied to the water surface and momentum from the wind is gradually transferred down through the water column. At the surface, wind generated currents are in the direction of the wind and gradually turn to the left of the wind direction (in Southern Hemisphere) through the water column. The Parramatta River Estuary is mostly shallow and has many complex branches which means that wind generated currents will generally follow the shoreline alignment in a broad direction towards where the wind is blowing.

Tidal patterns generally determine circulation in the Parramatta River estuary. The tide is semidiurnal and reverses every six hours. Spring tides in the harbour can have a tidal range of up to 1.6 m, and tidal forcing is strongest towards the Sydney Harbour heads. Current velocities recorded near Goat Island show that along estuaries velocities are typically 0.2m/s to 0.5m/s at peak flow and in the main channels (Cardno 2014, Freewater 2018, Xiao 2019).

The Gladesville Bridge Marina is located off the main channel of the Parramatta River and within a small embayment. Current velocities within the embayment are expected to be about 5-15cm/s, with velocities decreasing between the main channel and the shoreline (Cardno 2014). A small eddy (clockwise circulation within the embayment) may be present during the ebb with the flow separating off the Five Dock Point. Under strong wind conditions, this small clockwise eddy may strengthen under Westerly winds, stronger currents may also be present and flowing westward along the shoreline during winds from a South Easterly to North Easterly sector. It is noted that these river flow patterns are consistent with the results of water sample analysis as described in the Marine Ecology Study (Appendix J).

3.2 Impact of pontoons and piles on hydrodynamics near the Marina

Marina pontoons, piles or other structures as well as the berthed vessels have the potential to influence the water circulation within the marina.

Piles structures used for marina pontoons are expected to have a very small and localised impact on the flow due to their small diameters. They typically create localised friction and generate small turbulent eddies in their lee. The flow resistance due to a pile structure is dependent on the blocking of the flow by the piles (i.e. pile diameter and height through the water column). Small reduction in current velocities may then be observed directly behind each piles, their overall influence on circulation within the marina is expected to be negligible.

Berthed vessels and pontoons act as floating structures which typically affect the surface transport during the flood and ebb forcing it to pass under the floating structure. Figure 3.1 illustrates an example of the nearfield effect of a floating structure on tidal flow. In this instance the floating structure and the local depth are much larger than an individual pontoon/vessel and the depth near the GBM but it illustrates the process which is expected to occur.

With marina pontoons and vessels drafts in the order of 0.5m to 2m, in a depth of approximately 3m-8m, only a part of water column and flow is affected. The presence of pontoons and vessels produces a local zero-velocity surface boundary condition that dampens the current magnitudes especially in the upper water column and has the potential to slows down the water circulation process.

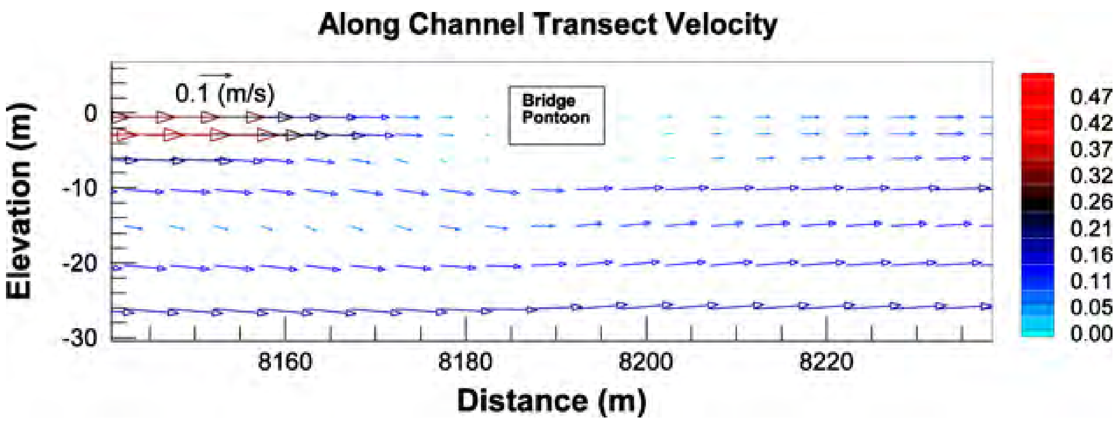

Figure 3.1 Example of nearfield effect of a bridge pontoon on currents (extracted from Khangaonkar &. Wang 2013)

3.3 Marina Flushing

A discussion of the GBM flushing and potential change in flushing with the proposed extension is presented in this section based on a review of the existing knowledge of physical processes (as presented in the previous sections). Further analysis can be undertaken with the use of a numerical hydrodynamic model and consideration for the transport of pollutants.

The term flushing used here describes the process by which water circulation and mixing will mitigate or prevent the concentration of pollutants in a selected area. The flushing or residence time refers to a duration, e.g. in hours or days, required for the pollutants concentration to drop to half (or decrease by a factor of e , i.e. e-folding time) or decreased to a specific level within a marina, harbour or estuary. Should the assessment of flushing time be required to inform the marine ecology assessment in more details, numerical hydrodynamic model simulations can be undertaken.

Adequate flushing of a marina is necessary for maintaining the water quality of the marina basin and adjacent waterway. Poorly flushed marinas can become stagnant and permit the concentration of pollutants from the marina facility and boats. Marina design features that promote flushing include: orientation of the marina towards natural water flow, provision of openings, minimising 'dead' water by creating curved surfaces, aligned entrance into prevailing winds … (GBRMPA, 1994)

The existing GBM layout is generally aligned with the main tidal flow and opened to the East where flood currents and winds from a South Easterly to North Easterly sectors are expected to increase mixing and circulation within the marina.

The proposed marina extension will conserve the same alignment and orientation with regards to the main current flow.

It is noted that the overall footprint of the marina floating structures (i.e. pontoons and vessels) is expected to approximately double, and that deeper draft vessels are also expected to be present. This has the potential to reduce water circulation within the marina particularly at low tide where the influence of the vessels and pontoons through the water column will be most significant.

Flushing of the marina is currently occurring based on weak (5cm/s -15cm/s) tidal currents and wind generated currents. The reduction in water circulation due to the pontoon extensions to the East is expected to be minimal. However, the increase in the number of vessels and increased draft of large vessels may locally affect the flushing. Nevertheless, with the marina layout maintaining its general alignment to the main tidal flow and promoting the maintenance of the small eddy during easterly currents (i.e. ebb flow), circulation along the shore (between the marina and the coastline), and opening towards the East (flood flow and wind generated currents) the proposed extension is expected to present similar flushing characteristics than the existing marina.

4. Metocean study methodology

An assessment of wave conditions at 6 locations (Table 4.1) within the Marina as illustrated in Figure 4.1 was undertaken.

Table 4.1 Coordinates and approximate water depth at the representative data reporting sites.

Site	World Geodetic System 1984 (WGS84)		Water depth (m, MSL)
	Latitude (N)	Longitude (E)	
GBM1	-33.843117°	151.145786°	9.0
GBM2	-33.842806°	151.146856°	7.7
GBM3	-33.842561°	151.147625°	8.7
GBM4	-33.843173°	151.147939°	4.4
GBM5	-33.843424°	151.147167°	4.8
GBM6	-33.843698°	151.146355°	4.6

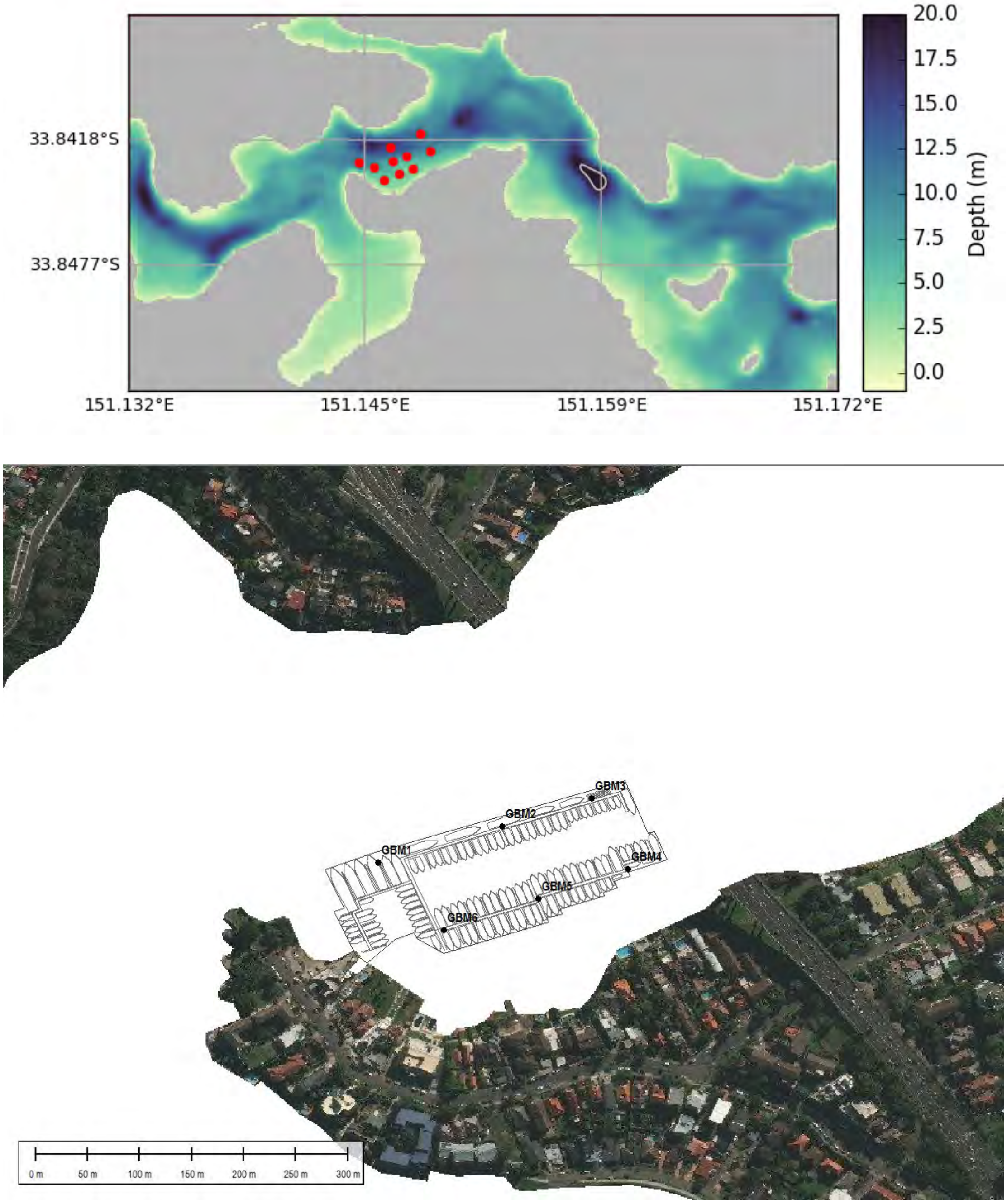

Figure 4.1 *Bathymetry map (top) and boundary limits (bottom) showing the area of interest and the reporting sites GBM1-6 within the proposed Marina.*

4.1 Metocean datasources

4.1.1 Wind data

Near-surface wind conditions were extracted from the hourly Climate Forecast System Reanalysis CFSR and CFSRv2 products (Saha et al. 2010) from the National Centers for Environmental Prediction (NCEP). These data span 39 years (1979 – 2017) at hourly intervals and 0.31° spatial resolution (approximately 30 km) until March 2011 and 0.20° (approximately 20 km) beyond April 2011.

Measured wind data from the Bureau of Meteorology station number 066022 in the vicinity of the area of interest (33.8551°S, 151.2254°E) [1] were used to adjust the CFSR/CFSRv2 data at the nearest model node as indicated in Figure 4.2.

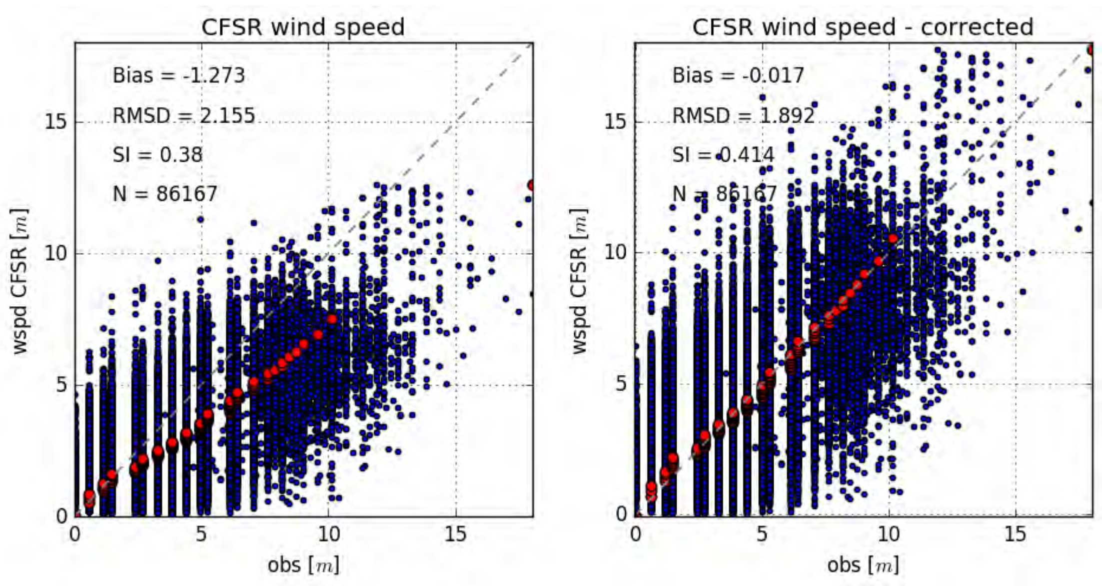

Figure 4.2 Quantile-quantile plots of the original CFSR wind speed at the nearest model node before (left) and after (right) correction.

4.1.2 Wave data

A 25-year wave hindcast (1993–2018) was undertaken using a modified version of SWAN[2] (Simulating WAves Nearshore).

4.1.2.1 Model description

SWAN is a third generation spectral wave model which solves the spectral action density balance equation (Booij, Ris, and Holthuijsen 1999). The model simulates

[1] http://www.bom.gov.au/products/IDN60801/IDN60801.94769.shtml

[2] Modified from SWAN version of the 40.91 release

the growth, refraction and decay of each frequency-direction component of the complete sea state, providing a realistic description of the wave field as it changes in time and space. Physical processes that are modelled include the generation of waves by surface wind, dissipation by white-capping, resonant nonlinear interaction between the wave components, bottom friction and depth limited breaking dissipation. A detailed description of the model equations, parameterisations and numerical schemes can be found in Holthuijsen et al. (2007) and in the SWAN documentation[3].

4.1.2.2 Model setup

SWAN was run in the non-stationary mode with all third generation physics included in the model. The source term parameterisations of Van der Westhuysen, Zijlema, and Battjes (2007) were employed and the Collins (1972) scheme was used for bottom friction with the default coefficient of 0.015. Wave breaking dissipation was simulated with the formulation of Battjes and Janssen (1978). The spectra were discretised with 36 directional bins (10° directional resolution) and up to 41 logarithmic frequencies *f* between 0.0971 and 4.834155 Hz.

The model domain was delimited by 151.132°E to 151.1718°E and 33.8535°S to 33.8360°S with resolution of 0.00015° (i.e. ~15 m).

The model was forced with adjusted CFSR/ CFSRv2 winds as described in Section 4.1.1.

Bathymetry to setup the different nests were constructed from a combination of Electronic Nautical Charts (ENCs) and the General Bathymetric Charts of the Oceans (GEBCO) global dataset (Weatherall et al. 2015) and available bathymetry survey near the Gladesville Bridge Marina.

4.1.2.3 Stationary model setup

In addition to the long term hindcast run, we undertook several scenarios in stationary modes by applying a range of uniform wind fields corresponding the extreme wind return period values and different water levels (Table 4.2). Wind growth, whitecap dissipation and quadruplet interaction source terms were switched off. Triad interactions were activated to account for nonlinear resonant interactions in the shoaling region. Consistent with the operational configuration,

[3] http://swanmodel.sourceforge.net/online_doc/online_doc.htm

we approximated depth-induced breaking dissipation and bottom friction using formulations from Battjes and Janssen (1978) and Collins (1972), respectively.

These stationary simulations were used to investigate the potential impact of climate change on metocean conditions near the Gladesville Bridge Marina. Quantitative estimate of the potential for change in wind patterns effect is limited at this stage and is not expected to be significant with regards to its associated impact on wind generated wave extreme within the Parramatta River (i.e. enclosed environment). Therefore, for this metocean study, consideration for the impact of climate change is mainly focused on sea level rise. Simulations were undertaken at a range of extreme water levels including for the 2050 and 2100 climate.

Table 4.2 Range of return period, wind direction and water levels used to run the stationary simulations.

Parameter	Values/levels considered
Return period (year)	1 and 50
Wind direction (from, centred)	North, North-East, East, South-East, South, South-West, West, North-West
Water level (m, AHD)	• MSL= 0 m AHD • HAT= 1.15m AHD • 50 year ARI - 2010 Design still water levels (m AHD)= 1.41mAHD • 50 year ARI - 2050 Design still water levels (m AHD)= 1.75mAHD • 50 year - 2100 Design still water levels (m AHD)= 2.25mAHD

4.2 Analytical methods

4.2.1 Wave

The wave spectra were post-processed to calculate wave statistics for the total wave field. One-dimensional frequency spectra were defined by integrating over all directions of the two-dimensional directional spectra:

$$E(f) = \int_{-\pi}^{\pi} E(f,\theta)d\theta. \tag{3.1}$$

Spectral moments were calculated as

$$m_x = \iint f^x E(f,\theta)df\, d\theta, \tag{3.2}$$

The significant wave height, H_s, mean direction at peak energy, Dpm, and peak wave period, T_p , are defined as:

$$H_s = 4\sqrt{m_0}, \tag{3.3}$$

$$Dpm = \tan^{-1}\frac{\int_{-\pi}^{\pi} E(f_p,\theta)\sin\theta\, d\theta}{\int_{-\pi}^{\pi} E(f_p,\theta)\cos\theta\, d\theta}, \tag{3.4}$$

$$T_p = 1/f_p, \tag{3.5}$$

where f_p is the peak wave frequency of the one-dimensional spectra and $E_n(f_p,\theta)$ is the energy contained in the peak wave frequency band.

4.2.2 Extreme

Omni-directional and directional return period values have been calculated from the hindcast time series of metocean parameters.

A *Peaks over Threshold* (POT) sampling method is used for event selection, applying the 95th percentile exceedance level as the threshold with a 24-hour window. For wind extreme value analysis (EVA), the 3-parameter Weibull distribution (shape parameters of 0.5 < k < 3.0) were applied, with Maximum Likelihood Method (MLM) used to find the best-fit of the sampled events to the model distribution. For wave EVA, the selected events were fitted to a Pareto distribution, with the location parameter fixed by the threshold and the MLM used to obtain the scale and shape parameters.

Note an arbitrary minimum number of 10 storm peaks has been was chosen for reliable distribution fitting. This results in specific directional return period values being omitted.

Bivariate return period values were calculated for significant wave height and peak period. The method of Repko et al. (2005) was employed, which considers the distribution of H_s and wave steepness, s. A joint probability distribution function (PDF) is calculated by multiplying marginal distributions of H_s and s (thus assuming they are independent), after which the PDF is transformed back into H_s/T_p space. In addition, a minimum wave steepness threshold of 0.005 is applied to exclude events with very long wave periods, which are not believed to be representative of extreme conditions.

The marginal distributions for H_s and s are estimated by fitting the POT values to a Weibull distribution using the maximum likelihood method (as implemented in the WAFO toolbox). Contours of the return period values were constructed from the joint PDF using the Inverse FORM method (Winterstein et al. 1993) at the return year levels.

5. Metocean study results

5.1 Wind climate

A summary of the adjusted wind speed statistics for the 10-minute mean at 10 m elevation at GBM1-6. is provided in Table 5.1. Note the hindcast wind speed and direction are identical at all sites GBM1-6.

The annual 10-min wind rose is illustrated in Figure 5.1, showing the annual predominance of winds coming from the S and NE quadrants.

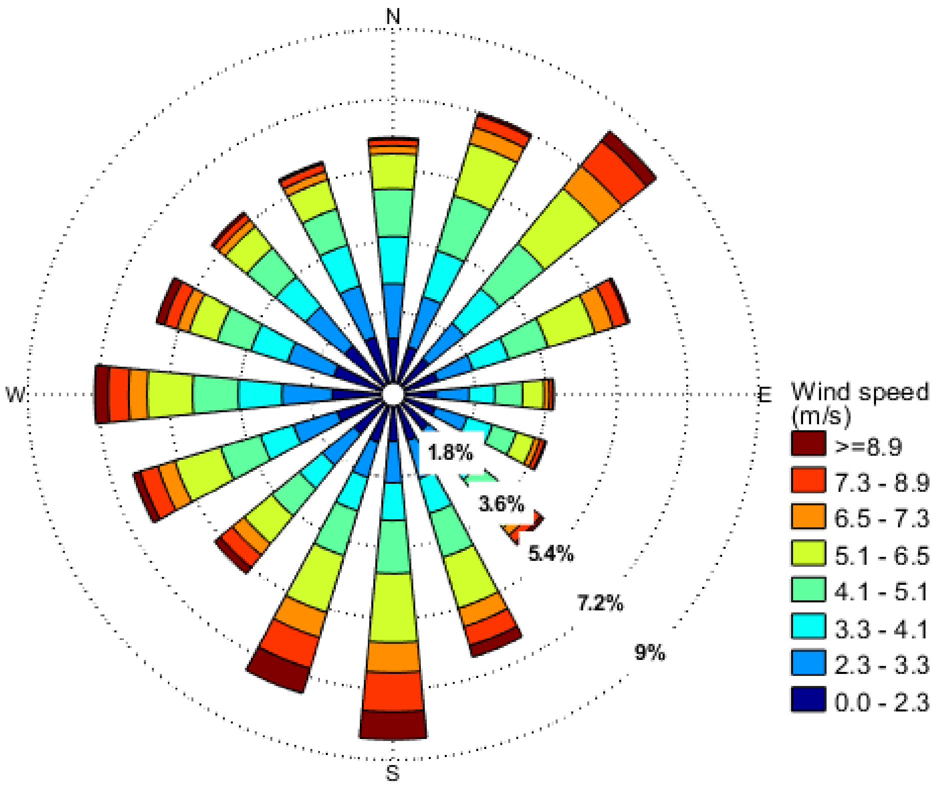

Figure 5.1 Annual wind rose plot (10-minute mean at 10 m AMSL) at GBM1-6. Sectors indicate the direction from which the winds blow.

Table 5.1 Annual and monthly 10-min wind speed statistics at GBM1-6.

Period (01 Jan 1993 – 31 Dec 2018)	10-min wind speed statistics [(1)]												
	10-min wind speed (m/s)			Exceedance percentile for 10-min wind speed (m/s)									Main [(4)] Direction(s)
	max	mean	std	p1	p5	p10	p50	p80	p90	p95	p98	p99	
January	16.90	4.61	2.12	0.63	1.46	1.99	4.46	6.36	7.39	8.29	9.37	10.25	NE S
February	17.28	4.38	2.12	0.53	1.22	1.75	4.19	6.14	7.22	8.10	9.17	9.98	NE SE S
March	17.05	4.15	2.10	0.59	1.20	1.66	3.91	5.79	6.88	7.96	9.17	10.17	NE SE S
April	19.63	3.94	2.00	0.59	1.23	1.66	3.64	5.46	6.53	7.60	8.96	10.02	S
May	17.31	4.11	2.12	0.68	1.36	1.77	3.72	5.77	6.97	8.09	9.46	10.38	S SW W NW
June	19.01	4.47	2.32	0.72	1.46	1.89	4.12	6.21	7.57	8.80	10.61	11.59	SW W NW
July	17.72	4.45	2.19	0.71	1.50	1.98	4.11	6.12	7.35	8.51	9.92	10.88	SW W NW
August	19.60	4.56	2.23	0.75	1.56	2.00	4.24	6.32	7.50	8.52	10.01	11.29	SW W NW
September	18.35	4.55	2.22	0.70	1.45	1.95	4.27	6.30	7.45	8.51	9.85	11.10	N W
October	17.02	4.53	2.22	0.65	1.38	1.87	4.29	6.27	7.48	8.55	9.92	11.05	N NE S
November	17.31	4.62	2.26	0.61	1.34	1.88	4.40	6.44	7.55	8.68	10.06	11.17	NE S
December	16.78	4.56	2.20	0.60	1.28	1.83	4.37	6.41	7.49	8.42	9.50	10.28	NE S
Summer[(2)]	17.31	4.48	2.18	0.60	1.31	1.82	4.27	6.24	7.35	8.33	9.53	10.48	NE S
Winter[(3)]	19.63	4.35	2.20	0.69	1.41	1.86	4.01	6.04	7.25	8.37	9.82	10.97	SW W NW
All	19.63	4.41	2.19	0.64	1.36	1.84	4.14	6.15	7.30	8.35	9.68	10.74	NE S

Notes:

(1) All statistics derived from hindcast wind data (10-min mean at 10 m AMSL) for the period 01 January 1993 to 31 December 2018.

(2) Summer: April to September.

(3) Winter: October to March.

(4) Main directions are those with greater than 15% occurrence and represent directions from which the winds approach.

5.2 Wave climate

A summary of the total significant wave height statistics (H_s) at sites GBM1-6 are provided in Table 5.2-Table 5.7.

Wave roses for the annual total significant wave height are presented in Figure 5.2-Figure 5.7, showing the predominance of waves incoming from the W and NE sectors.

Table 5.2 Annual and monthly total significant wave height statistics at GBM1.

Period (01 Jan 1993 – 31 Dec 2018)	Total significant wave height statistics [1]													
	Total significant wave height (m)				Exceedance percentile for total significant wave height (m)									Main [4] Direction(s)
	min	max	mean	std	p1	p5	p10	p50	p80	p90	p95	p98	p99	
January	0.00	0.23	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE
February	0.00	0.23	0.04	0.03	0.00	0.00	0.01	0.04	0.07	0.09	0.11	0.13	0.14	NE SE
March	0.00	0.18	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.12	0.13	NE SE W
April	0.00	0.19	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.09	0.11	0.13	NE W
May	0.00	0.22	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.09	0.11	0.14	0.16	W
June	0.00	0.29	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.13	0.15	0.17	W
July	0.00	0.22	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.15	0.16	W
August	0.00	0.23	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.16	NE W
September	0.00	0.21	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.16	NE W
October	0.00	0.21	0.05	0.03	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE W
November	0.00	0.20	0.05	0.04	0.00	0.00	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE W
December	0.00	0.21	0.05	0.04	0.00	0.00	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE
Summer[2]	0.00	0.23	0.05	0.03	0.00	0.00	0.01	0.04	0.07	0.09	0.11	0.13	0.15	NE
Winter[3]	0.00	0.29	0.04	0.04	0.00	0.01	0.01	0.03	0.07	0.10	0.12	0.14	0.16	NE W
All	0.00	0.29	0.05	0.04	0.00	0.00	0.01	0.04	0.07	0.10	0.12	0.14	0.15	NE W

Notes: (1)

All statistics derived from hindcast wave data for the period 01 January 1993 to 31 December 2018.

(2) Summer: April to September.

(3) Winter: October to March.

(4) Main directions are those with greater than 15% occurrence and represent directions from which the waves approach.

Table 5.3 Annual and monthly total significant wave height statistics at GBM2.

Period (01 Jan 1993 – 31 Dec 2018)	Total significant wave height statistics (1)													
	Total significant wave height (m)				Exceedance percentile for total significant wave height (m)									Main (4) Direction(s)
	min	max	mean	std	p1	p5	p10	p50	p80	p90	p95	p98	p99	
January	0.00	0.22	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE S
February	0.00	0.22	0.04	0.03	0.00	0.00	0.01	0.04	0.07	0.09	0.11	0.13	0.14	NE S
March	0.00	0.21	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.08	0.10	0.12	0.13	NE S W
April	0.00	0.22	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.13	0.14	NE S W
May	0.00	0.26	0.04	0.04	0.00	0.00	0.01	0.03	0.07	0.10	0.12	0.15	0.17	W
June	0.00	0.28	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.14	0.17	0.19	W
July	0.00	0.26	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.13	0.16	0.18	W
August	0.00	0.25	0.05	0.04	0.00	0.01	0.01	0.04	0.09	0.11	0.13	0.16	0.17	NE W
September	0.00	0.24	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.13	0.16	0.18	NE W
October	0.00	0.21	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.16	NE W
November	0.00	0.21	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.16	NE S
December	0.00	0.21	0.05	0.04	0.00	0.00	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE S
Summer(2)	0.00	0.22	0.05	0.03	0.00	0.00	0.01	0.04	0.08	0.10	0.11	0.14	0.15	NE S
Winter(3)	0.00	0.28	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.13	0.16	0.17	NE W
All	0.00	0.28	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.15	0.16	NE S W

Notes: (1)

All statistics derived from hindcast wave data for the period 01 January 1993 to 31 December 2018.

(2) Summer: April to September.

(3) Winter: October to March.

(4) Main directions are those with greater than 15% occurrence and represent directions from which the waves approach.

Table 5.4 Annual and monthly total significant wave height statistics at GBM3.

Period (01 Jan 1993 – 31 Dec 2018)	Total significant wave height statistics [1]													
	Total significant wave height (m)				Exceedance percentile for total significant wave height (m)									Main [4] Direction(s)
	min	max	mean	std	p1	p5	p10	p50	p80	p90	p95	p98	p99	
January	0.00	0.22	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE S
February	0.00	0.22	0.05	0.03	0.00	0.00	0.01	0.04	0.07	0.09	0.11	0.13	0.14	NE S
March	0.00	0.23	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.08	0.10	0.12	0.13	NE S W
April	0.00	0.24	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.13	0.15	NE S W
May	0.00	0.28	0.05	0.04	0.00	0.00	0.01	0.03	0.07	0.10	0.13	0.16	0.18	W
June	0.00	0.27	0.05	0.05	0.00	0.01	0.01	0.04	0.09	0.12	0.15	0.18	0.20	W
July	0.00	0.28	0.05	0.04	0.00	0.01	0.01	0.04	0.09	0.12	0.14	0.17	0.19	W
August	0.00	0.27	0.05	0.04	0.00	0.01	0.01	0.04	0.09	0.12	0.14	0.17	0.18	NE W
September	0.00	0.25	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.13	0.16	0.18	NE W
October	0.00	0.22	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.15	0.16	NE W
November	0.00	0.23	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.15	0.16	NE
December	0.00	0.21	0.05	0.04	0.00	0.00	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE S
Summer[2]	0.00	0.23	0.05	0.04	0.00	0.00	0.01	0.04	0.08	0.10	0.12	0.14	0.15	NE S
Winter[3]	0.00	0.28	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.13	0.16	0.18	NE W
All	0.00	0.28	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.15	0.17	NE W

Notes: (1)

All statistics derived from hindcast wave data for the period 01 January 1993 to 31 December 2018.

(2) Summer: April to September.

(3) Winter: October to March.

(4) Main directions are those with greater than 15% occurrence and represent directions from which the waves approach.

Table 5.5 Annual and monthly total significant wave height statistics at GBM4.

Period (01 Jan 1993 – 31 Dec 2018)	Total significant wave height statistics (1)													
	Total significant wave height (m)				Exceedance percentile for total significant wave height (m)									Main (4) Direction(s)
	min	max	mean	std	p1	p5	p10	p50	p80	p90	p95	p98	p99	
January	0.00	0.21	0.04	0.03	0.00	0.01	0.01	0.04	0.07	0.09	0.11	0.13	0.15	NE SW
February	0.00	0.19	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.12	0.13	NE SW
March	0.00	0.17	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.07	0.09	0.11	0.12	NE SW
April	0.00	0.19	0.03	0.03	0.00	0.00	0.01	0.03	0.05	0.07	0.09	0.11	0.13	NE SW W
May	0.00	0.20	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.09	0.11	0.14	0.15	NE SW W
June	0.00	0.25	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.13	0.16	0.18	SW W
July	0.00	0.22	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.13	0.16	0.17	W
August	0.00	0.23	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.11	0.13	0.15	0.17	NE W
September	0.00	0.24	0.05	0.04	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.15	0.17	NE W
October	0.00	0.21	0.05	0.03	0.00	0.00	0.01	0.04	0.07	0.09	0.11	0.14	0.15	NE W
November	0.00	0.21	0.04	0.03	0.00	0.00	0.01	0.04	0.07	0.10	0.11	0.13	0.15	NE SW
December	0.00	0.20	0.04	0.03	0.00	0.00	0.01	0.04	0.07	0.10	0.12	0.14	0.15	NE SW
Summer(2)	0.00	0.21	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.09	0.11	0.13	0.14	NE SW
Winter(3)	0.00	0.25	0.05	0.04	0.00	0.00	0.01	0.03	0.07	0.10	0.12	0.15	0.17	NE SW W
All	0.00	0.25	0.04	0.04	0.00	0.00	0.01	0.03	0.07	0.09	0.11	0.14	0.15	NE SW W

Notes: (1)

All statistics derived from hindcast wave data for the period 01 January 1993 to 31 December 2018.

(2) Summer: April to September.

(3) Winter: October to March.

(4) Main directions are those with greater than 15% occurrence and represent directions from which the waves approach.

Table 5.6 Annual and monthly total significant wave height statistics at GBM5.

Period (01 Jan 1993 – 31 Dec 2018)	Total significant wave height statistics (1)													
	Total significant wave height (m)				Exceedance percentile for total significant wave height (m)									Main (4) Direction(s)
	min	max	mean	std	p1	p5	p10	p50	p80	p90	p95	p98	p99	
January	0.00	0.22	0.05	0.03	0.00	0.01	0.01	0.04	0.07	0.10	0.12	0.14	0.15	NE S
February	0.00	0.20	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.12	0.13	NE S
March	0.00	0.18	0.03	0.03	0.00	0.00	0.01	0.03	0.05	0.07	0.09	0.11	0.12	NE S
April	0.00	0.17	0.03	0.03	0.00	0.00	0.01	0.03	0.05	0.07	0.08	0.10	0.11	NE S W
May	0.00	0.20	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.12	0.14	NE SW W
June	0.00	0.26	0.04	0.04	0.00	0.01	0.01	0.03	0.07	0.09	0.11	0.14	0.15	SW W
July	0.00	0.19	0.04	0.03	0.00	0.01	0.01	0.03	0.07	0.09	0.11	0.14	0.15	SW W NW
August	0.00	0.20	0.05	0.03	0.00	0.01	0.01	0.04	0.08	0.10	0.12	0.13	0.15	NE W
September	0.00	0.21	0.05	0.04	0.00	0.01	0.01	0.04	0.07	0.10	0.12	0.14	0.15	NE W
October	0.00	0.21	0.04	0.03	0.00	0.00	0.01	0.04	0.07	0.09	0.11	0.13	0.14	NE S W
November	0.00	0.19	0.04	0.03	0.00	0.00	0.01	0.04	0.07	0.09	0.11	0.13	0.15	NE S
December	0.00	0.21	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.10	0.12	0.14	0.15	NE S
Summer(2)	0.00	0.22	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.09	0.11	0.13	0.14	NE S
Winter(3)	0.00	0.26	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.09	0.11	0.13	0.15	NE W
All	0.00	0.26	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.09	0.11	0.13	0.14	NE S W

Notes: (1)

All statistics derived from hindcast wave data for the period 01 January 1993 to 31 December 2018.

(2) Summer: April to September.

(3) Winter: October to March.

(4) Main directions are those with greater than 15% occurrence and represent directions from which the waves approach.

Table 5.7 Annual and monthly total significant wave height statistics at GBM6.

Period (01 Jan 1993 – 31 Dec 2018)	Total significant wave height statistics (1)													
	Total significant wave height (m)				Exceedance percentile for total significant wave height (m)									Main (4) Direction(s)
	min	max	mean	std	p1	p5	p10	p50	p80	p90	p95	p98	p99	
January	0.00	0.22	0.04	0.04	0.00	0.00	0.01	0.03	0.07	0.10	0.12	0.14	0.15	NE S
February	0.00	0.21	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.12	0.13	NE S
March	0.00	0.18	0.03	0.03	0.00	0.00	0.01	0.03	0.05	0.07	0.09	0.11	0.12	NE S
April	0.00	0.15	0.03	0.02	0.00	0.00	0.01	0.02	0.04	0.06	0.07	0.09	0.10	NE S NW
May	0.00	0.21	0.03	0.03	0.00	0.00	0.01	0.02	0.05	0.06	0.08	0.10	0.12	NE S W NW
June	0.00	0.28	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.09	0.11	0.12	S W NW
July	0.00	0.17	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.09	0.11	0.12	S W NW
August	0.00	0.19	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.11	0.13	NE W NW
September	0.00	0.19	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.09	0.10	0.12	0.14	NE NW
October	0.00	0.22	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.09	0.10	0.12	0.14	NE S NW
November	0.00	0.19	0.04	0.03	0.00	0.00	0.01	0.03	0.07	0.09	0.11	0.13	0.14	NE S
December	0.00	0.21	0.04	0.04	0.00	0.00	0.01	0.03	0.07	0.10	0.12	0.14	0.15	NE S
Summer(2)	0.00	0.22	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.09	0.11	0.13	0.14	NE S
Winter(3)	0.00	0.28	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.07	0.09	0.11	0.12	NE S W NW
All	0.00	0.28	0.04	0.03	0.00	0.00	0.01	0.03	0.06	0.08	0.10	0.12	0.13	NE S NW

Notes: (1)

All statistics derived from hindcast wave data for the period 01 January 1993 to 31 December 2018.

(2) Summer: April to September.

(3) Winter: October to March.

(4) Main directions are those with greater than 15% occurrence and represent directions from which the waves approach.

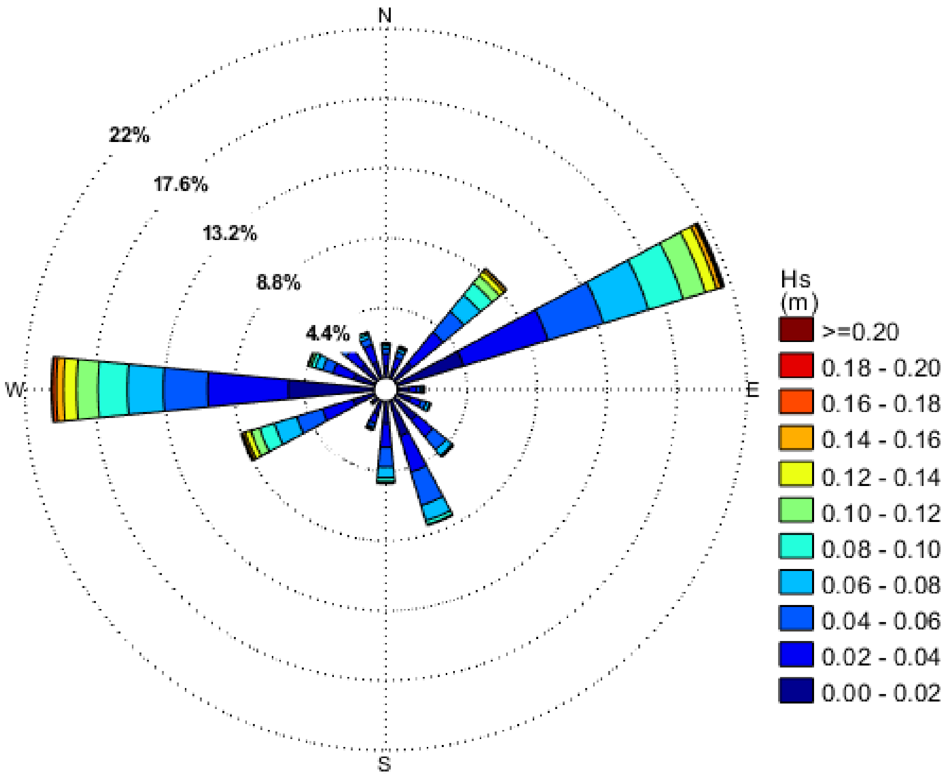

Figure 5.2 Annual wave rose plot for the total significant wave height at GBM1. Sectors indicate the direction from which waves approach.

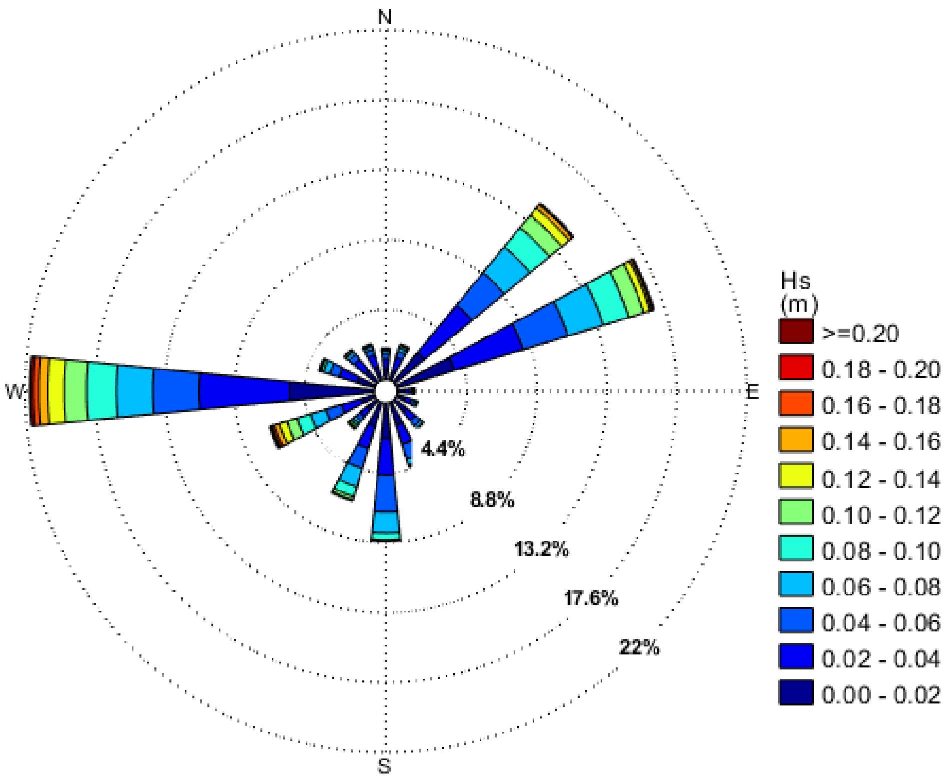

Figure 5.3 Annual wave rose plot for the total significant wave height at GBM2. Sectors indicate the direction from which waves approach.

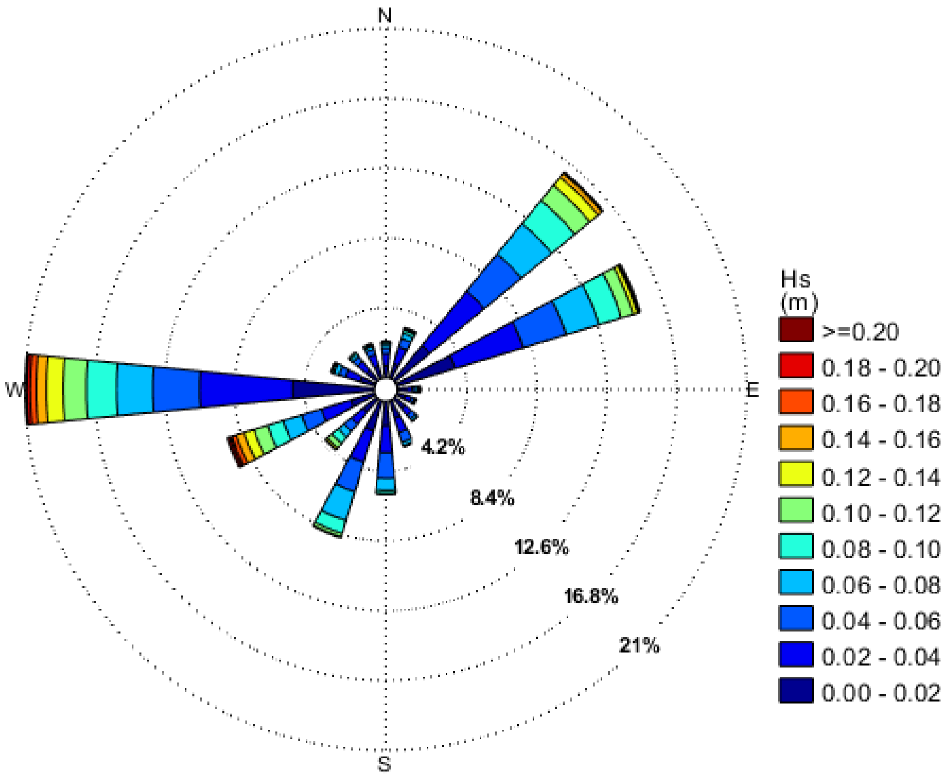

Figure 5.4 Annual wave rose plot for the total significant wave height at GBM3. Sectors indicate the direction from which waves approach.

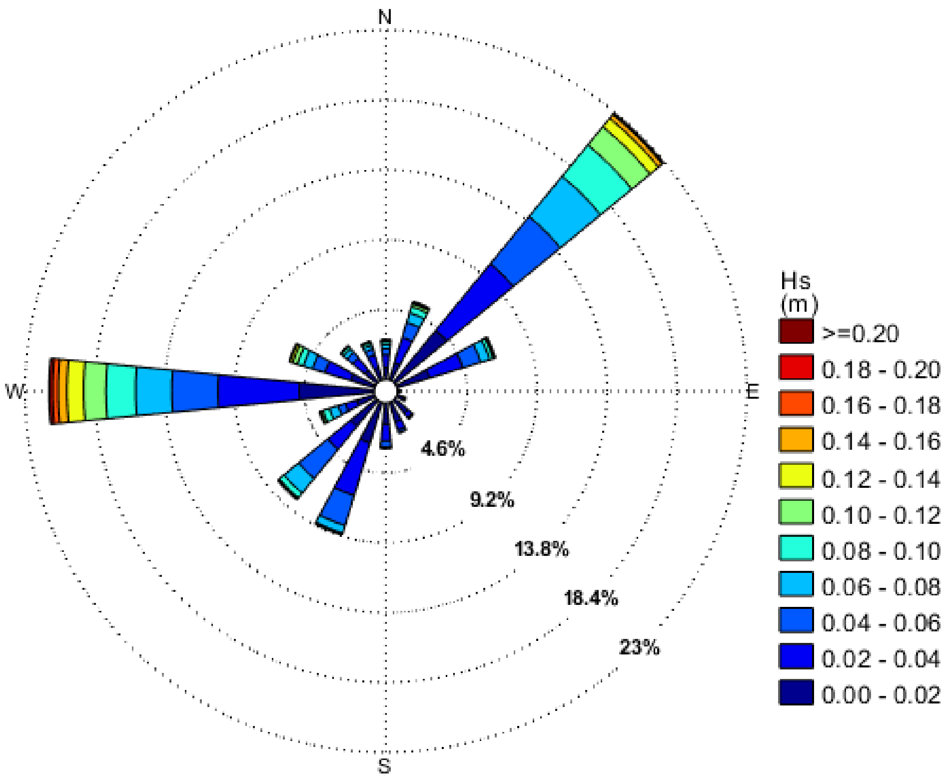

Figure 5.5 Annual wave rose plot for the total significant wave height at GBM4. Sectors indicate the direction from which waves approach.

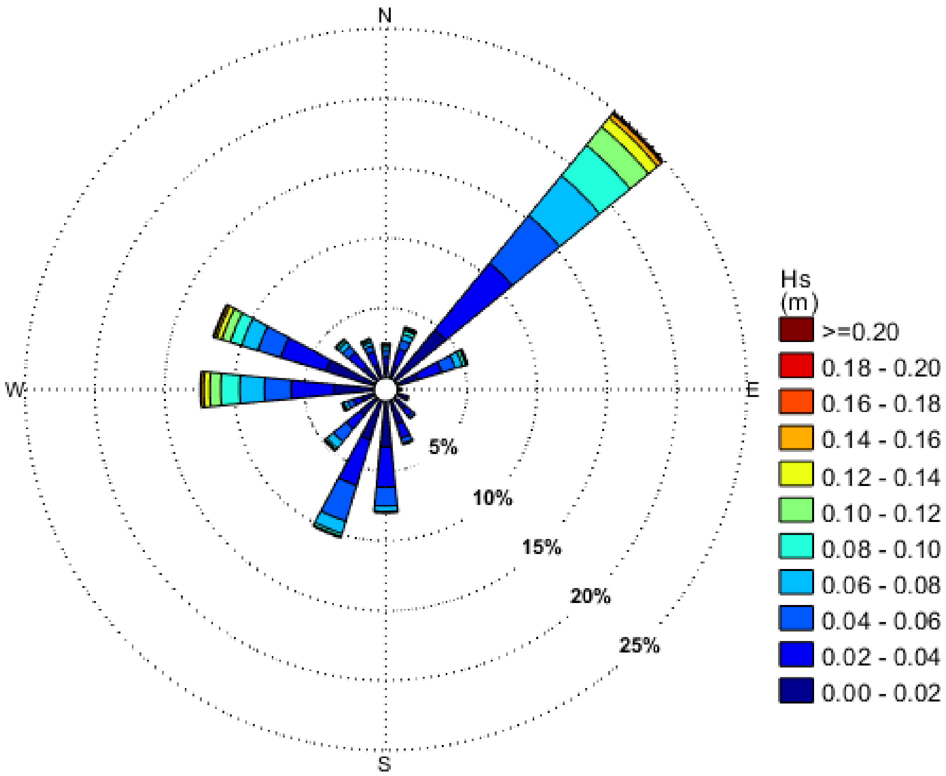

Figure 5.6 Annual wave rose plot for the total significant wave height at GBM5. Sectors indicate the direction from which waves approach.

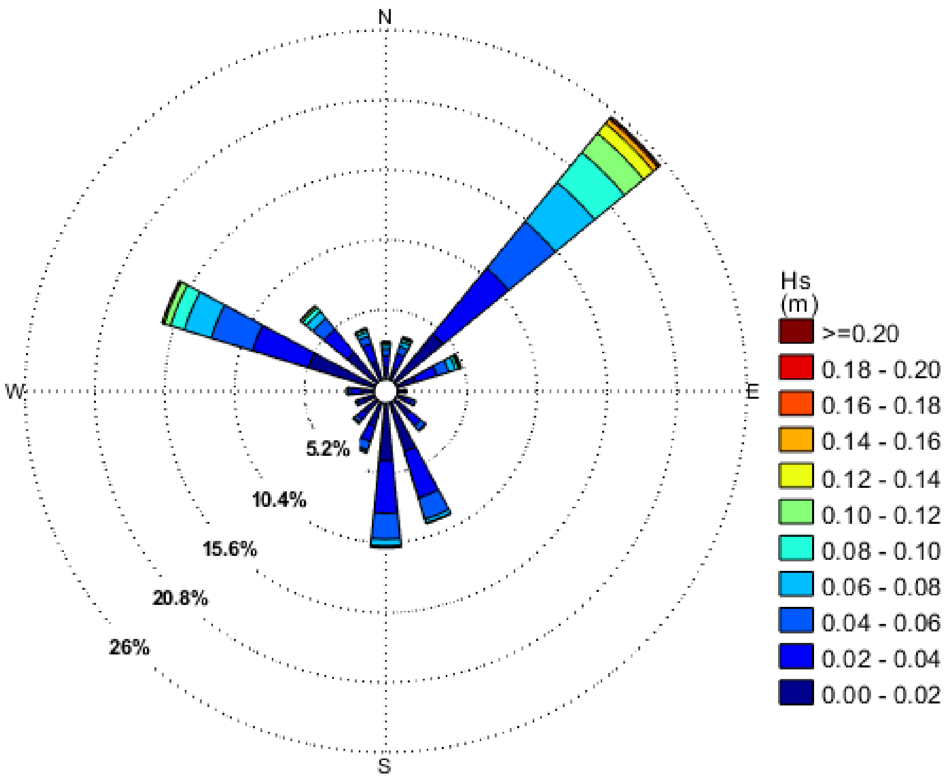

Figure 5.7 Annual wave rose plot for the total significant wave height at GBM6. Sectors indicate the direction from which waves approach.

5.3 Extreme metocean statistics

5.3.1 Long-term hindcast

The directional return period values estimated from the 25-year hindcast duration for wind and wave extremes are given in Table 5.8 to Table 5.14 for 1, 10, 50 and 100-year return periods. Note an arbitrary minimum number of 10 storm peaks has been chosen for reliable distribution fitting. This results in specific directional return period values being omitted. Contour plot of omni-directional bi-variate return period values for significant wave height and peak wave period are presented in Figure 5.8 to Figure 5.13.

Table 5.8 Annual independent omni-directional extreme criteria for wind at GBM1-6.

Parameter	Return Period (year)	Direction (from)								
		N	NE	E	SE	S	SW	W	NW	Omni
10-min wind speed	1	9.80	12.66	8.79	10.93	14.58	12.01	12.43	10.62	16.08
	10	12.37	15.75	10.82	14.65	18.25	17.06	15.95	14.43	19.94
	50	14.08	17.80	12.20	17.32	20.68	20.76	18.31	17.09	22.56
	100	14.80	18.66	12.79	18.48	21.71	22.39	19.30	18.24	23.68

Table 5.9 Annual independent omni-directional extreme criteria for waves at GBM1.

Parameter	Return Period (year)	Direction (from)								
		N	NE	E	SE	S	SW	W	NW	Omni
Hs (m)	**1**	0.10	0.19	0.12	0.09	0.11	0.09	0.19	0.10	0.20
	10	0.13	0.23	0.18	0.13	0.14	0.11	0.22	0.13	0.24
	50	0.13	0.25	0.21	0.15	0.15	0.13	0.23	0.13	0.25
	100	0.14	0.26	0.22	0.16	0.16	0.14	0.23	0.14	0.26
Tp (s)	**1**	1.06	1.53	1.25	0.99	0.98	1.07	1.61	1.06	1.61
	10	1.17	1.68	1.47	1.10	1.07	1.36	1.74	1.17	1.73
	50	1.19	1.75	1.57	1.16	1.11	1.69	1.79	1.21	1.79
	100	1.20	1.78	1.61	1.18	1.12	1.85	1.80	1.21	1.81

Table 5.10 Annual independent omni-directional extreme criteria for waves at GBM2.

Parameter	Return Period (year)	Direction (from)								
		N	NE	E	SE	S	SW	W	NW	Omni
Hs (m)	**1**	0.10	0.18	0.12	0.09	0.11	0.12	0.21	0.09	0.21
	10	0.12	0.22	0.17	0.12	0.14	0.17	0.24	0.12	0.25
	50	0.13	0.25	0.20	0.13	0.16	0.20	0.26	0.13	0.26
	100	0.13	0.25	0.20	0.14	0.17	0.20	0.26	0.14	0.27
Tp (s)	**1**	1.06	1.53	1.26	0.94	1.05	1.12	1.64	1.03	1.67
	10	1.14	1.72	1.47	1.04	1.15	1.28	1.77	1.15	1.82
	50	1.15	1.82	1.55	1.08	1.20	1.35	1.82	1.18	1.89
	100	1.16	1.85	1.57	1.09	1.22	1.37	1.84	1.19	1.92

Table 5.11 Annual independent omni-directional extreme criteria for waves at GBM3.

Parameter	Return Period (year)	Direction (from)								
		N	NE	E	SE	S	SW	W	NW	Omni
Hs (m)	**1**	0.11	0.18	0.12	0.08	0.11	0.14	0.22	0.09	0.22
	10	0.13	0.21	0.17	0.11	0.14	0.19	0.26	0.12	0.26
	50	0.14	0.23	0.19	0.13	0.16	0.21	0.28	0.13	0.28
	100	0.14	0.23	0.20	0.14	0.17	0.22	0.28	0.14	0.29
Tp (s)	**1**	1.08	1.47	1.27	0.92	1.03	1.23	1.67	1.00	1.65
	10	1.18	1.59	1.47	1.02	1.15	1.40	1.82	1.13	1.79
	50	1.21	1.65	1.57	1.06	1.21	1.47	1.88	1.17	1.86
	100	1.22	1.67	1.60	1.08	1.23	1.49	1.89	1.19	1.88

Table 5.12 Annual independent omni-directional extreme criteria for waves at GBM4.

Parameter	Return Period (year)	Direction (from)								
		N	NE	E	SE	S	SW	W	NW	Omni
Hs (m)	1	0.12	0.18	-	0.05	0.07	0.11	0.20	0.11	0.20
	10	0.15	0.21	-	0.08	0.10	0.16	0.23	0.15	0.23
	50	0.16	0.23	-	0.09	0.13	0.21	0.23	0.17	0.24
	100	0.16	0.24	-	0.10	0.14	0.23	0.24	0.18	0.25
Tp (s)	1	1.17	1.49	-	0.69	0.83	1.06	1.59	1.10	1.60
	10	1.29	1.63	-	0.84	0.99	1.24	1.71	1.26	1.74
	50	1.32	1.70	-	0.89	1.08	1.36	1.74	1.33	1.80
	100	1.33	1.73	-	0.91	1.12	1.40	1.75	1.35	1.82

Table 5.13 Annual independent omni-directional extreme criteria for waves at GBM5.

Parameter	Return Period (year)	Direction (from)								
		N	NE	E	SE	S	SW	W	NW	Omni
Hs (m)	1	0.12	0.18	-	0.06	0.09	0.10	0.17	0.12	0.19
	10	0.14	0.22	-	0.09	0.11	0.15	0.20	0.16	0.22
	50	0.15	0.24	-	0.10	0.13	0.18	0.20	0.18	0.24
	100	0.15	0.25	-	0.11	0.14	0.19	0.21	0.19	0.24
Tp (s)	1	1.15	1.50	-	0.76	0.92	0.99	1.47	1.17	1.54
	10	1.26	1.64	-	0.87	1.02	1.14	1.54	1.30	1.65
	50	1.30	1.70	-	0.93	1.07	1.22	1.56	1.36	1.71
	100	1.31	1.72	-	0.95	1.09	1.24	1.57	1.38	1.72

Table 5.14 Annual independent omni-directional extreme criteria for waves at GBM6.

Parameter	Return Period (year)	Direction (from)								
		N	NE	E	SE	S	SW	W	NW	Omni
Hs (m)	1	0.12	0.19	0.06	0.07	0.08	0.07	0.11	0.14	0.19
	10	0.14	0.23	0.08	0.10	0.11	0.11	0.12	0.17	0.22
	50	0.15	0.25	0.09	0.12	0.13	0.14	0.13	0.18	0.24
	100	0.15	0.25	0.10	0.13	0.14	0.15	0.13	0.18	0.25
Tp (s)	1	1.15	1.55	0.89	0.82	0.90	0.80	1.24	1.27	1.57
	10	1.24	1.71	1.02	0.95	1.00	0.95	1.37	1.34	1.71
	50	1.27	1.79	1.11	1.02	1.06	1.03	1.41	1.36	1.78
	100	1.28	1.81	1.15	1.05	1.08	1.06	1.42	1.37	1.80

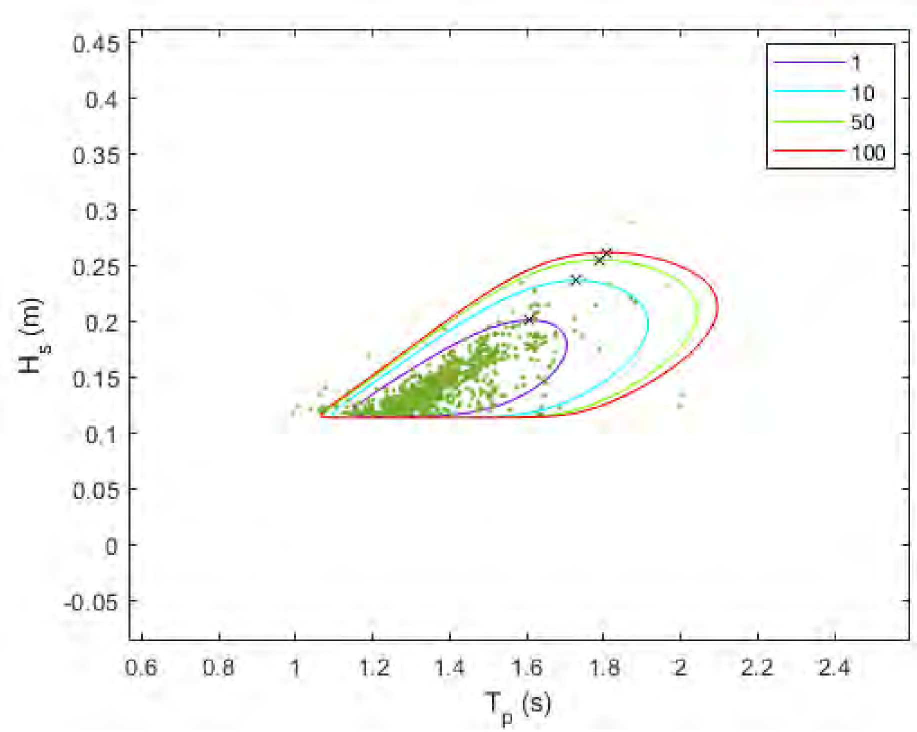

Figure 5.8 *Contour plot of omni-directional bi-variate (Hs-Tp) return period values for 1, 10, 50 and 100-year ARIs. The dark crosses correspond to the estimated deterministic Hs and associated Tp return period values for each ARI indicated in the legend at GBM1.*

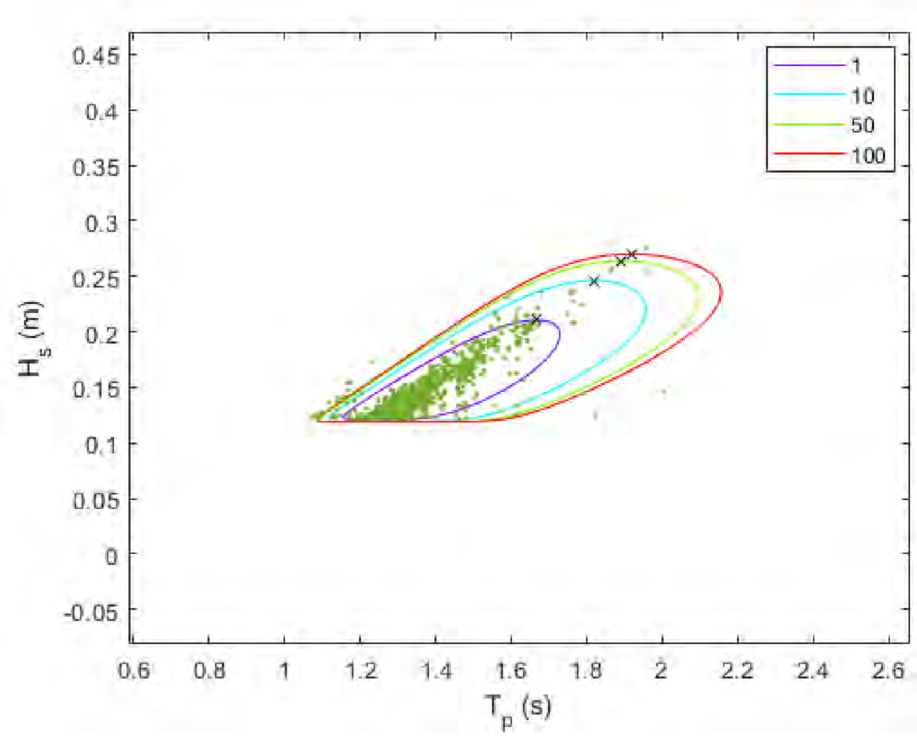

Figure 5.9 *Contour plot of omni-directional bi-variate (Hs-Tp) return period values for 1, 10, 50 and 100-year ARIs. The dark crosses correspond to the estimated deterministic Hs and associated Tp return period values for each ARI indicated in the legend at GBM2.*

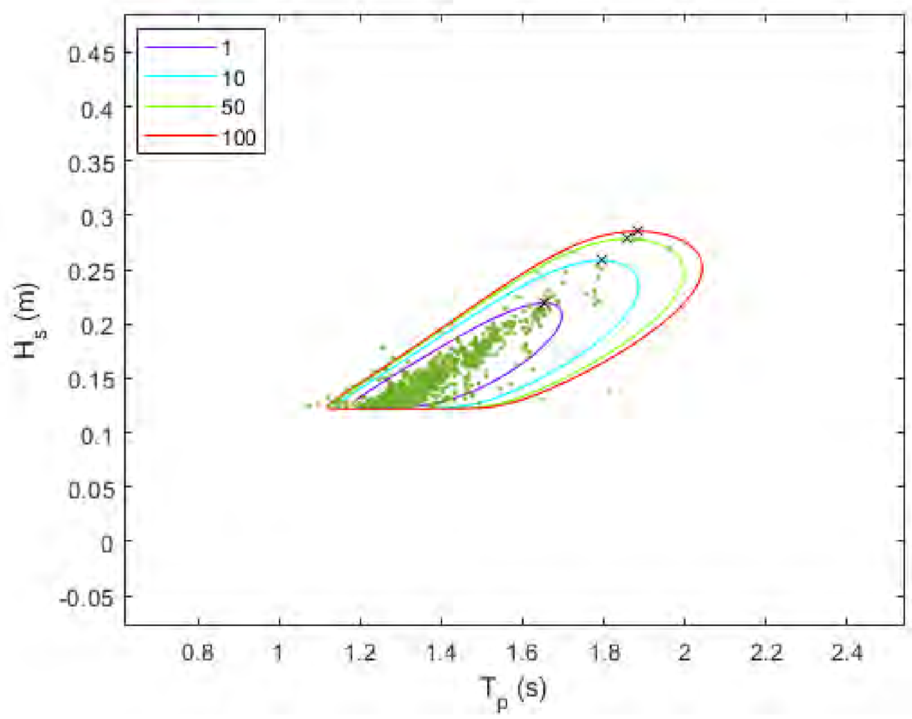

Figure 5.10 Contour plot of omni-directional bi-variate (Hs-Tp) return period values for 1, 10, 50 and 100-year ARIs. The dark crosses correspond to the estimated deterministic Hs and associated Tp return period values for each ARI indicated in the legend at GBM3.

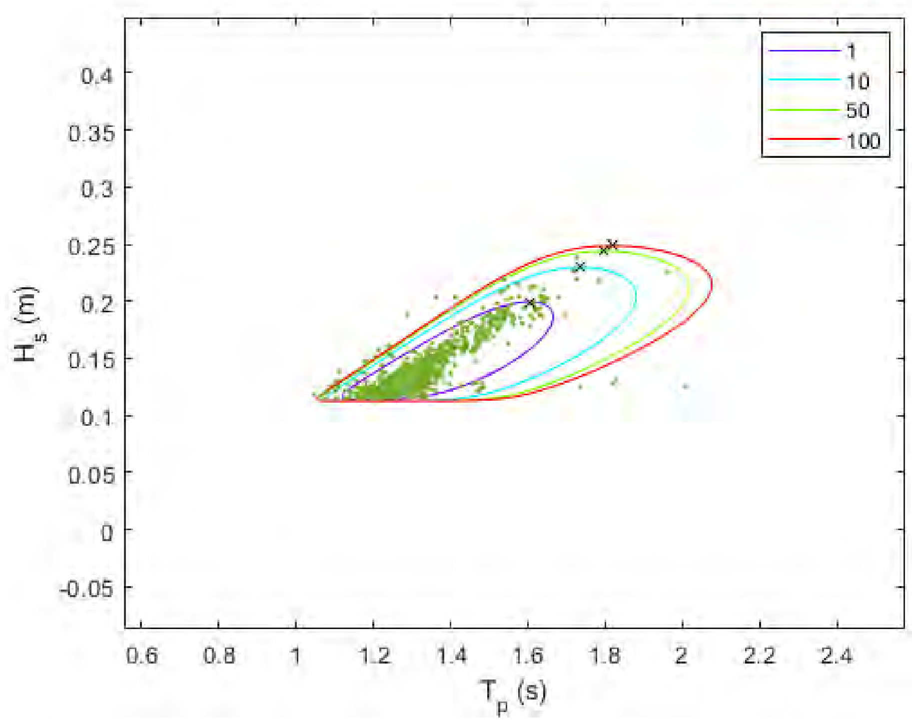

Figure 5.11 Contour plot of omni-directional bi-variate (Hs-Tp) return period values for 1, 10, 50 and 100-year ARIs. The dark crosses correspond to the estimated deterministic Hs and associated Tp return period values for each ARI indicated in the legend at GBM4.

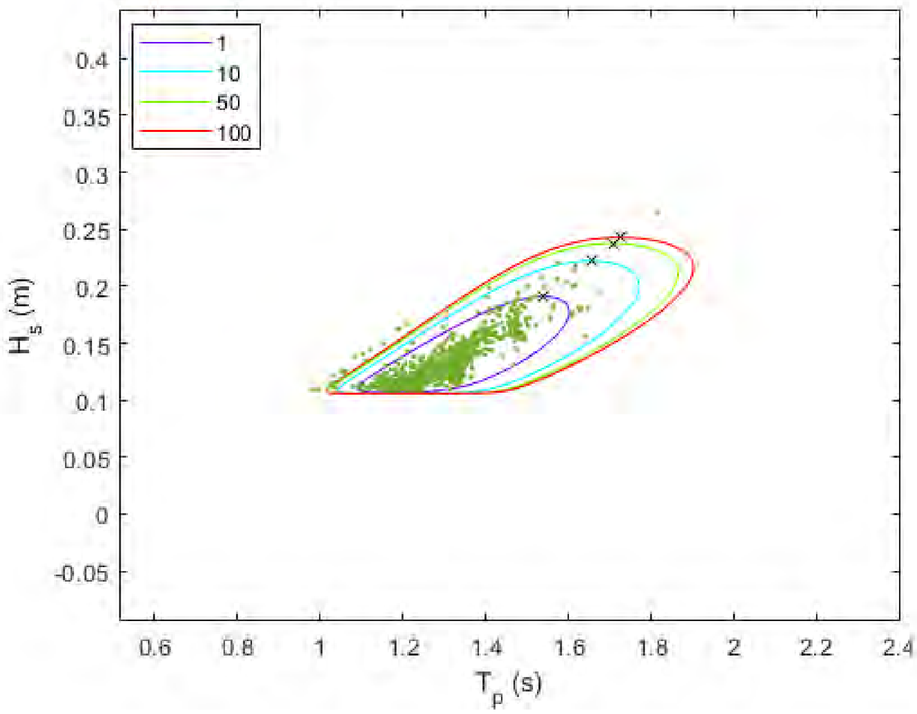

Figure 5.12 Contour plot of omni-directional bi-variate (Hs-Tp) return period values for 1, 10, 50 and 100-year ARIs. The dark crosses correspond to the estimated deterministic Hs and associated Tp return period values for each ARI indicated in the legend at GBM5.

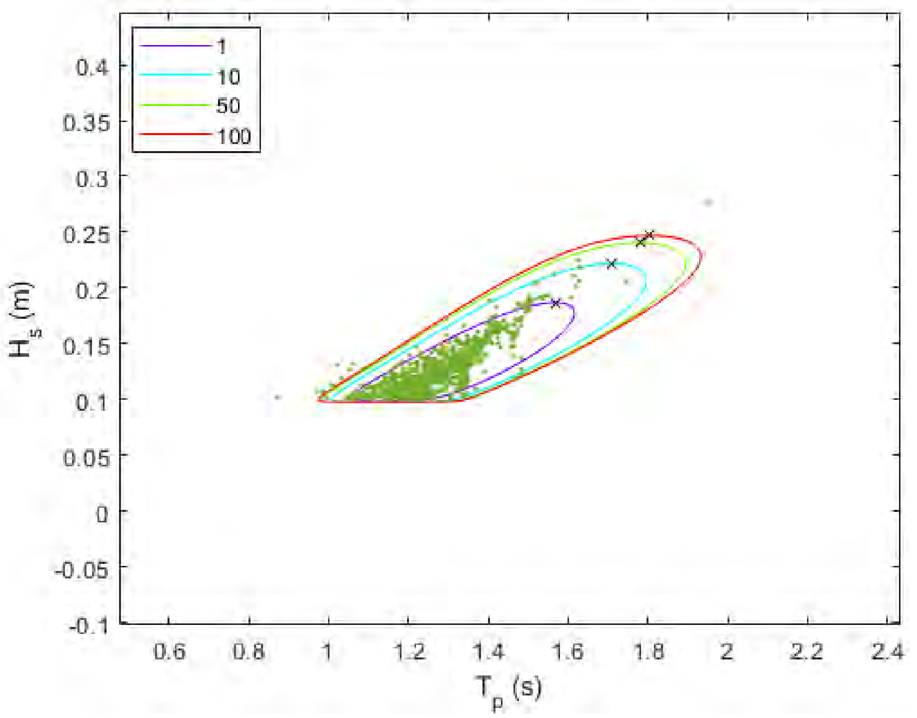

Figure 5.13 Contour plot of omni-directional bi-variate (Hs-Tp) return period values for 1, 10, 50 and 100-year ARIs. The dark crosses correspond to the estimated deterministic Hs and associated Tp return period values for each ARI indicated in the legend at GBM6.

5.3.2 Stationary simulations – Influence of increased water level

Assessment of the effect of increased water level (including storm surge and sea level rise) on extreme wave conditions was undertaken using a set of wave model stationary simulations.

The directional return period values were estimated for the 1, 10 , 50 and 100 year ARI Wind speed for each 45 degrees wind direction sector and a range of extreme water levels: i.e. MSL, HAT, 50 year ARI storm tide for the 2010, 2050 and 2100 climate. Results are presented for location GBM 2 in Table 5.15 to Table 5.19.

The Significant Wave Height (Hs) pattern for NE, E and W winds for the 1 and 50-year ARIs are shown in Figure 5.14 for a water Level is set at 0 m AHD and in Figure 5.15 for a water level of 1.41mAHD.

Results show that the influence of an elevated water level may increase the design wave height by about 50% and the wave period by about 30% between MSL and HAT for the extreme wind case scenarios (a maximum of 100% increase in wave height is observed for the 100 year ARI wave height from the SW, from Hs= 0.18m for MSL to Hs = 0.36m for HAT and above).

Above the HAT level, there is only a small increase in wave height (~5%) associated with increased storm surge and sea level rise. This plateauing (in the increase) is mostly due to the fact that the actual fetch is not changing significantly once the water level goes above HAT level (only the actual depth is increased). It should be noted that the increase water level did not include potential change in the shoreline, this is considered a reasonable assumption at this stage as the land near at the shoreline is mostly heavily developed and engineered (flooding of large built areas is not expected).

Table 5.15 Directional extreme criteria for waves at GBM2 for main wind directions - water level to MSL (0mAHD)

WL = 0 mAHD	Wind Direction							
Hs RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	0.12	0.15	0.15	0.14	0.12	0.12	0.14	0.14
10	0.16	0.18	0.18	0.17	0.15	0.15	0.15	0.16
50	0.19	0.20	0.20	0.20	0.17	0.17	0.17	0.19
100	0.20	0.22	0.21	0.21	0.18	0.18	0.19	0.20
Tp RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	1.21	1.26	1.28	1.33	1.25	1.21	1.58	1.41
10	1.34	1.37	1.38	1.47	1.38	1.36	1.35	1.39
50	1.46	1.48	1.48	1.50	1.48	1.44	1.38	1.51
100	1.47	1.49	1.50	1.51	1.49	1.48	1.47	1.53

Table 5.16 Directional extreme criteria for waves at GBM2 for main wind directions - water level to HAT (+ 1.15mAHD)

WL = +1.15 mAHD	Wind Direction							
Hs RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	0.12	0.21	0.12	0.11	0.15	0.16	0.19	0.13
10	0.16	0.27	0.15	0.16	0.20	0.25	0.26	0.20
50	0.19	0.32	0.18	0.20	0.24	0.33	0.31	0.25
100	0.20	0.34	0.19	0.22	0.26	0.36	0.34	0.27
Tp RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	1.22	1.63	1.35	0.95	1.09	1.63	1.62	1.18
10	1.35	1.80	1.48	1.11	1.24	1.83	1.83	1.37
50	1.47	1.95	1.57	1.23	1.34	2.01	1.98	1.51
100	1.48	1.98	1.62	1.27	1.37	2.12	2.01	1.58

Table 5.17 Directional extreme criteria for waves at GBM2 for main wind directions - water level to 50 year ARI storm tide 2010 climate (+ 1.41mAHD)

WL = +1.41 mAHD	Wind Direction							
Hs RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	0.12	0.21	0.12	0.11	0.15	0.16	0.19	0.13
10	0.16	0.27	0.15	0.16	0.20	0.25	0.26	0.20
50	0.19	0.32	0.18	0.20	0.24	0.32	0.31	0.25
100	0.20	0.34	0.19	0.22	0.25	0.36	0.34	0.27
Tp RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	1.22	1.63	1.35	0.95	1.09	1.63	1.62	1.18
10	1.35	1.80	1.48	1.11	1.24	1.81	1.83	1.37
50	1.47	1.95	1.57	1.23	1.34	1.99	1.98	1.51
100	1.48	1.98	1.62	1.27	1.37	2.11	2.01	1.58

Table 5.18 Directional extreme criteria for waves at GBM2 for main wind directions - water level to 50 year ARI storm tide 2050 climate (+ 1.75mAHD)

WL = +1.75 mAHD	**Wind Direction**							
Hs RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	0.12	0.21	0.12	0.11	0.15	0.16	0.19	0.13
10	0.16	0.27	0.15	0.16	0.20	0.25	0.27	0.20
50	0.19	0.32	0.18	0.20	0.24	0.33	0.32	0.25
100	0.20	0.34	0.19	0.22	0.25	0.37	0.34	0.27
Tp RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	1.22	1.63	1.35	0.95	1.09	1.64	1.63	1.18
10	1.35	1.80	1.48	1.11	1.24	1.87	1.84	1.38
50	1.47	1.95	1.58	1.23	1.34	2.03	1.98	1.51
100	1.49	1.98	1.63	1.27	1.37	2.12	2.02	1.58

Table 5.19 Directional extreme criteria for waves at GBM2 for main wind directions - water level to 50 year ARI storm tide 2100 climate (+ 2.25mAHD)

WL = +2.25 mAHD	**Wind Direction**							
Hs RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	0.12	0.21	0.12	0.11	0.15	0.16	0.19	0.13
10	0.16	0.27	0.15	0.16	0.20	0.25	0.27	0.20
50	0.19	0.32	0.18	0.20	0.24	0.33	0.32	0.25
100	0.20	0.35	0.19	0.22	0.25	0.37	0.34	0.27
Tp RPV	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
1	1.22	1.63	1.35	0.95	1.09	1.64	1.63	1.19
10	1.35	1.80	1.49	1.11	1.24	1.95	1.85	1.38
50	1.47	1.95	1.58	1.23	1.35	2.10	1.99	1.51
100	1.49	1.98	1.63	1.27	1.37	2.11	2.04	1.59

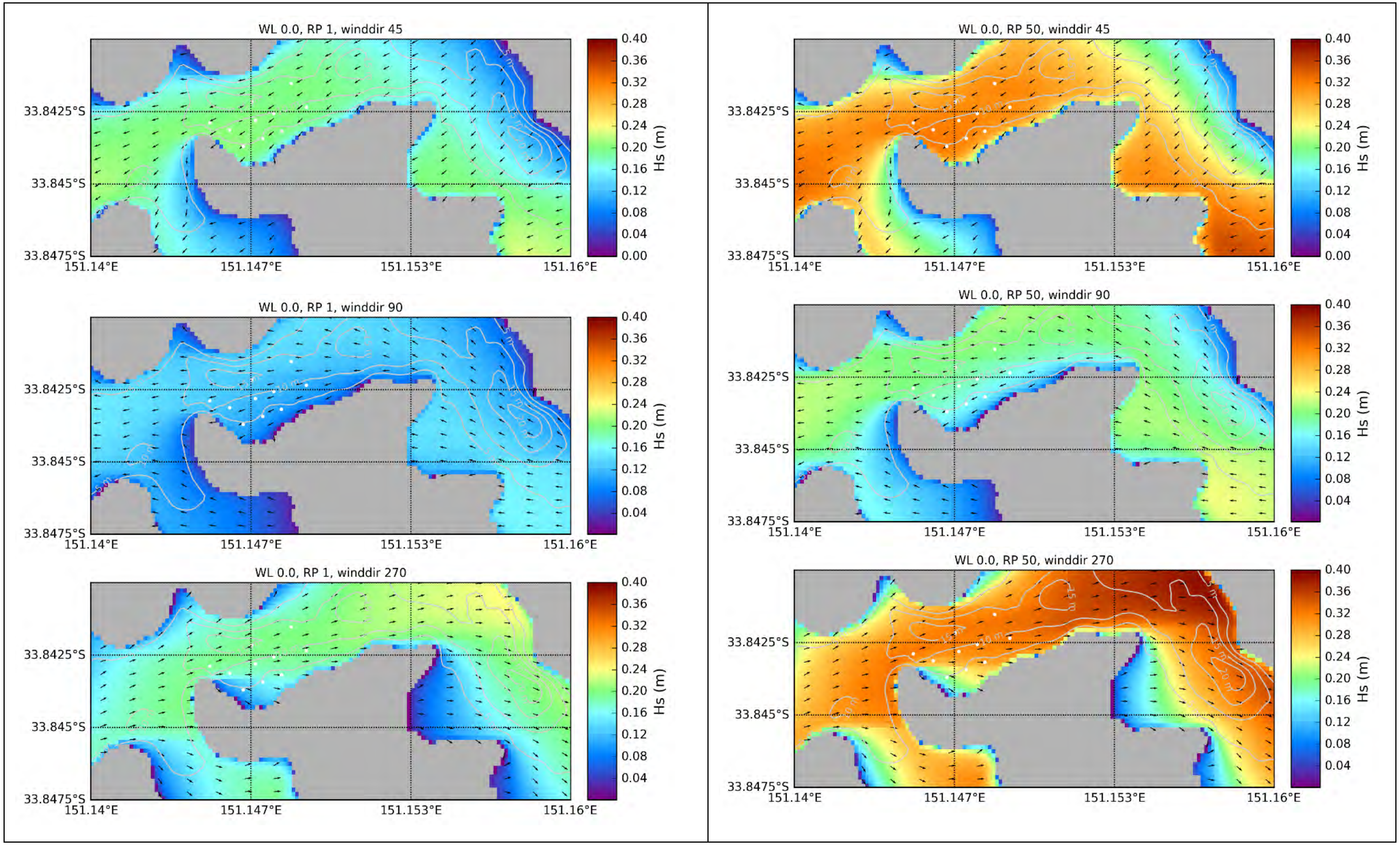

Figure 5.14 Significant Wave Height (Hs) maps for NE, E and W winds and for the 1 and 50-year ARIs. Water Level is set at 0 m AHD.

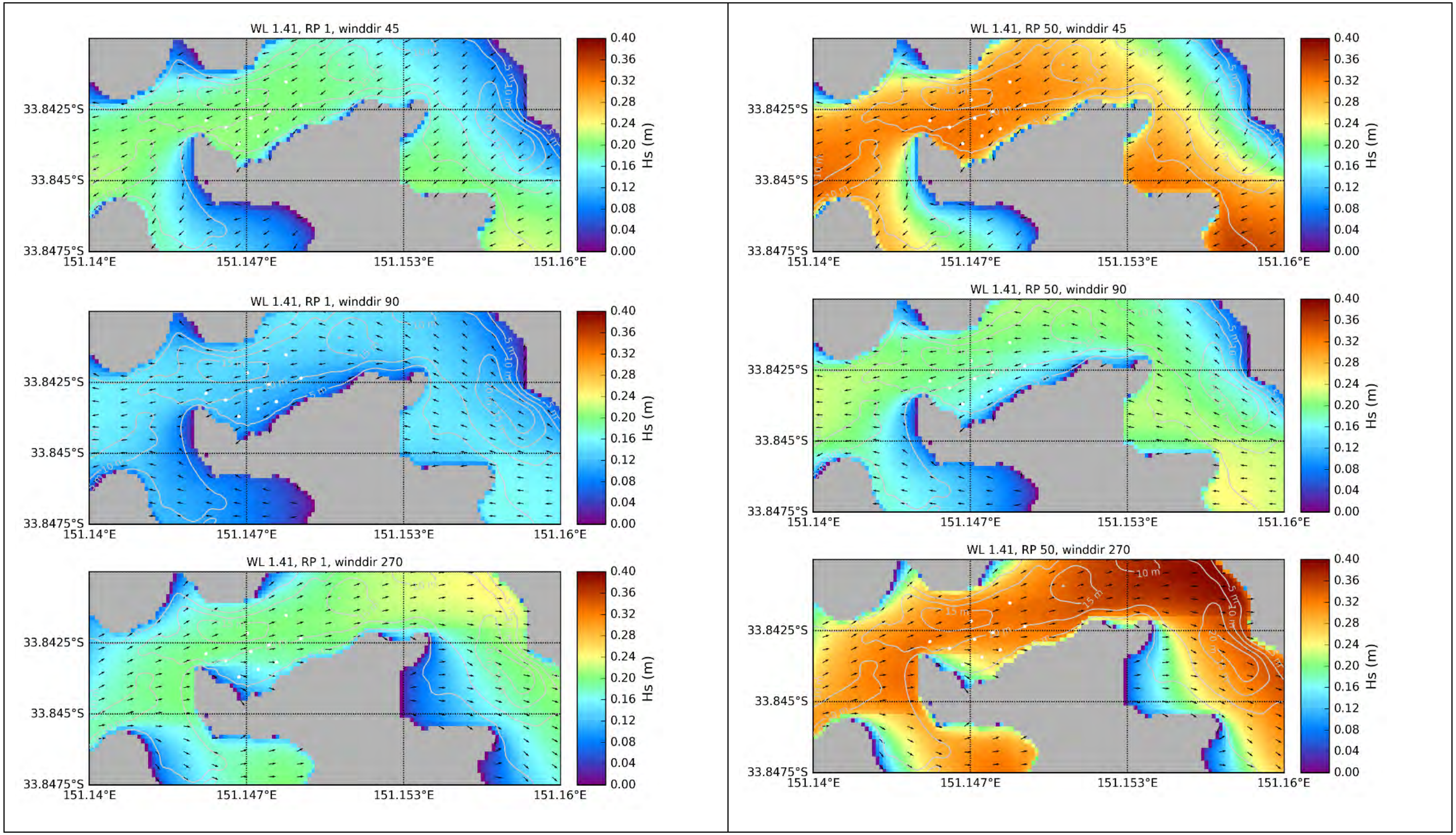

Figure 5.15 Significant Wave Height (Hs) maps for NE, E and W winds and for the 1 and 50-year ARIs. Water Level is set at 1.41 m AHD (50 year ARI - 2010 Design still water levels).

5.3.3 Vessel wake waves

Boat traffic within the Parramatta River typically include Powercraft, Monohull Charter, Catamaran Charter, Work Boat/Fishing Boat , RiverCat and Jet skis (Patterson Britton and Partners, 2000). It is noted that Jet Skis have been banned in Sydney Harbour since 2000. All vessels propelled through the water will generate some form of wash/boat wake. Additional information on boat wash is also provided in Appendix F - Marine Safety and Navigation Report.

There are regular RiverCat services along the Parramatta River to Circular Quay with a number of wharves at various points along the river. It is understood that boat wash from the RiverCat and harbour ferries has been implicated in shoreline erosion along the estuary (Webb, McKeown and Associates, 2007). The negative impacts of boat wash, particularly from the RiverCat and ferries, was also highlighted in a number of comments provided in relation to the condition of seawalls, bank erosion and the loss of foreshore vegetation.

The long wave period associated with RiverCat wash significantly limits the range of remedial options available. Environmentally favourable solutions, such as coir logs and jute matting are unsuitable for wave climates with wave periods larger than around three seconds, such as those created by wash from the RiverCat.

A high level assessment of wake wave generated by a RiverCat operating in the Parramatta River was undertaken based on MacFarlane (2012) Wake wave predictor (https://amcstaff.utas.edu.au/maritime-engineering/wave-wake-predictor).

As discussed in MacFarlane (2012) three types of waves are within the overall wave train generated by a vessel:

Wave A: defined as the leading diverging wave, which is the wave that will possess the longest period. It is often the waves with long periods that create the greatest issues within sheltered waterways (particularly bank erosion), which makes the quantification of these waves very important.

Wave B: defined as the most significant wave following the leading wave (Wave A). The period will be shorter than the leading wave, but often not by a large margin, whereas the height is very often greater than the leading wave.

Wave C: it is common for a group of short period divergent waves to be generated and Wave C is defined as being the highest wave within this group. This wave always follows Waves A and B, hence will possess the shortest wave period of these three key waves.

As presented in 'Table B.1 List of typical vessel operations in Australian sheltered waterways MacFarlane (2012), the typical RiverCat operating in Sydney Harbour is the River Cat 35 m Catamaran Passenger (46500kg), with a typical vessel speed between 4 knots and 10 knots.

Considering a water depth of 10m and lateral distance to the vessel sailing line of 100m (middle of the Parramatta River to the marina) and a vessel speed of 10knots, the calculated wake wave parameters are:

- Wave A: wave height 0.04m , wave period 2.8s
- Wave B: wave height 0.10m , wave period 2.5s
- Wave C: wave height 0.10m , wave period 2.1s

Additional sensitivity calculation show that the wave height and period increase with increasing vessel speed, e.g. with a vessel speed of 12 knots, the wake wave parameters are:

- Wave A: wave height 0.06m , wave period 4.1s
- Wave B: wave height 0.10m, wave period 3.3s
- Wave C: wave height 0.13m , wave period 2.1s

These waves are of similar magnitude to the ambient wind generated waves at the site however they are generally smaller than the extreme wave events. Nevertheless, there are provided here for information should it be useful for certain aspect of the design.

It is noted however that a no-wash zone is located between the Gladesville Bridge and Five Dock Point and therefore the speed at which vessels must travel is predicated on the no wash zone. RiverCats and other vessels will travel at lower speed near the Gladesville Bridge Marina than used in the above wave assessment.

The Appendix F - Marine Safety and Navigation Report also highlighted that the No Wash Zone (Low Wash Zone) has been in place since 1993 (26 years) and recent written comments from RMS in the Marine safety plan 2014 indicate it will not be altered from its current location on the river.

5.3.4 Extreme Wave Conditions Discussion

Based on the 25-year wave hindcast duration, design wave conditions have been determined for the 1, 10, 50 and 100-year return periods (see Table 3.10 to Table 3.16). Assessment of the impact of an increased water level was undertaken using a set of extreme wind wave modelling simulations.

Design wave conditions at GBM2 is presented again in Table 5.20 together with an upper estimate of wave height and peak period for extreme water levels.

Table 5.20 Directional design wave conditions at GBM2.

	Return Period	Direction (from)									Extreme Water Level (+50% Hs, +30% Tp)
	(year)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**Omni**	**Omni**
Hs (m)	**1**	0.1	0.18	0.12	0.09	0.11	0.12	0.21	0.09	0.21	0.32
	10	0.12	0.22	0.17	0.12	0.14	0.17	0.24	0.12	0.25	0.38
	50	0.13	0.25	0.2	0.13	0.16	0.2	0.26	0.13	0.26	0.39
	100	0.13	0.25	0.2	0.14	0.17	0.2	0.26	0.14	0.27	0.41
Tp (s)	**1**	1.1	1.5	1.3	0.9	1.1	1.1	1.6	1.0	1.7	2.2
	10	1.1	1.7	1.5	1.0	1.2	1.3	1.8	1.2	1.8	2.4
	50	1.2	1.8	1.6	1.1	1.2	1.4	1.8	1.2	1.9	2.5
	100	1.2	1.9	1.6	1.1	1.2	1.4	1.8	1.2	1.9	2.5

The criteria and parameters used to define a 'good' wave climate for a marina are set out in AS 3962- – Guidelines for the Design of Marinas, see Table 5.21. In the case of the Gladesville Bridge Marina, it is noted that the design local wind sea wave periods are generally less than 2 seconds and wave height satisfy the conditions for 'good' wave climate and is also within the criteria for 'excellent' wave climate (using a 0.75 multiplier for wave height).

It is noted however that with consideration for elevated water levels and/or storm surge/sea level rise, wave peak period may exceed 2 seconds and wave height may reach 0.32m for the 1-year ARI and 0.39m for the 50-year ARI. The conditions for 'good' wave climate are then not be satisfied for the once a year wave event criteria and for the Beam seas greater than 2seconds for the once in 50 year event.

It is also noted that as shown in Section 5.3.3 , wake waves generated by passing vessels (e.g. Rivercats) are not expected to be above the criteria for 'good' wave climate especially as the area is a no-wash zone and passing vessels are expected to minimise the generation of wake waves.

Table 5.21 Criteria for a good wave climate in small craft harbour AS 3962- – Guidelines for the Design of Marinas (Source: Adapted from MERCER, A.G., ISAACSON, M. and MULCAHY, M.W. Design wave climate in small craft harbours. 18th Conference on Coastal Engineering, Capetown. 1982

CRITERIA FOR A 'GOOD' WAVE CLIMATE IN SMALL CRAFT HARBOUR		
Direction and peak period of design harbour wave	**Significant wave height (Hs)**	
	Wave event exceeded once in 50 years	**Wave event exceeded once a year**
Head seas less than 2s	Conditions not likely to occur during this event	Less than 0.3m wave height
Head seas greater than 2s	Less than 0.6m wave height	Less than 0.3m wave height
Oblique seas greater than 2s	Less than 0.4m	Less than 0.3m wave height
Beam seas less than 2s	Conditions not likely to occur during this event	Less than 0.3m wave height
Beam seas greater than 2s	Less than 0.25 wave height	Less than 0.15m wave height

NOTE: For criteria for an 'excellent' wave climate multiply wave height by 0.75, and for a 'moderate' wave climate multiply wave height by 1.25. For vessels of less than 20 m in length, the most severe wave climate should satisfy moderate conditions. For vessels larger than 20 m in length, the wave climate may be more severe.

5.3.5 Impact of Marina Additions on Wave Climate

This study describes the wave climate near the marina in terms of ambient and extreme conditions. The proposed alteration and additions of the marina, including the pontoons, piles and berthed vessels are not expected to affect the local wave conditions besides providing some wave sheltering to the shoreline directly behind the proposed extension similarly to the existing marina.

With wave periods around 2-3seconds floating pontoons/vessels are expected to act as wave attenuator and reduce the wave propagation to the shoreline by about 20% to 80% depending on the number of pontoons/vessels and their drafts (WRL Ron Cox Floating Breakwaters comm, Cox et al 2009, Wiegel 1960).

6. References

Australian Standard 2001 - AS3962 - Guidelines for Design of Marinas, Standards Australia International, Second Edition.

AECOM 2010 Parramatta River Estuary Processes Study. Prepared for Parramatta River Estuary Management Committee

Battjes, J. A., and J. P. F. M. Janssen. 1978. "Energy Loss and Set-up Due to Breaking Random Waves." Coastal Engineering Proceedings 1 (16). https://icce-ojs-tamu.tdl.org/icce/index.php/icce/article/view/3294.

Booij, NRRC, R. C. Ris, and Leo H. Holthuijsen. 1999. "A Third-Generation Wave Model for Coastal Regions: 1. Model Description and Validation." Journal of Geophysical Research: Oceans 104 (C4): 7649–7666.

Cardno 2008 Parramatta River Estuary Data Compilation and Review Study. Prepared for Parramatta River Estuary Management Committee.

Cardno 2013 Parramatta River Estuary Coastal Zone Management Study. Parramatta River Estuary Data Compilation and Review Study. Prepared for Parramatta River Estuary Management Committee.

Cardno 2014 Sydney Harbour Ecological Response Model Model Set-up, Calibration and Water Quality Investigations 59914067/R001 Sydney Prepared for Greater Sydney Local Land Services13 August 2014

CSIRO 2009 Marine and atmospheric research sea level rise website,

www.cmar.csiro.au/sealevel/, accessed 26 October 2009

Collins, J. 1972. "Prediction of Shallow Water Spectra." Journal of Geophysical Research 77 (15): 2693–2707.

Cox R. - Floating Breakwaters - Water Research Laboratory

Cox R., I. Coghln and C. Kerry 2009 . Floating Breakwater performance in irregular waves with particular emphasis on wave transmission and reflection, energy dissipation , motions and restraining forces. DOI: 10.1142/9789814282024_0032 Conference: Coastal Structures 2007 - 5th Coastal Structures International Conference, CST07

Department of Environment, Climate Change and Water (DECCW) 2010 Coastal Risk Management Guide - Incorporating sea level rise benchmarks in coastal risk assessments

Freewater, P. 2018 Sydney Harbour Estuary Processes Study - Stage 2 Detailed Studies of Vulnerabilities and Opportunities. Report prepared for Greater Sydney Local Land Services, June 2018

Forristall, George Z. 1978. "On the Statistical Distribution of Wave Heights in a Storm." Journal of Geophysical Research: Oceans 83 (C5): 2353–2358.

Forristall, George Z.. 2000. “Wave Crest Distributions: Observations and Second-Order Theory.” Journal of Physical Oceanography 30 (8).

Great Barrier Reef Marine Park Authority (GBRMPA) 1994. Environmental Guidelines for Marinas in the Great Barrier Reef Marine Park

Holthuijsen, L. H., N. Booij, R. C. Ris, I. J. Haagsma, A. T. M. M. Kieftenburg, E. E. Kriezi, M. Zijlema, and A. J. van der Westhuysen. 2007. SWAN Cycle III Version 40.51. Technical Documentation. 2600 GA Delft The Netherlands: Delft. http://iod.ucsd.edu/~falk/modeling/swantech.pdf.

ISO. 2015. “19901-1:2015(En) Petroleum and Natural Gas Industries - Specific Requirements for Offshore Structures - Part 1: Metocean Design and Operating Conditions.” British Standards Institute.

Khangaonkar T. and T. Wang 2013. Potential alteration of fjordal circulation due to a large floating structure—Numerical investigation with application to Hood Canal basin in Puget Sound , Applied Ocean Research 39 (2013) 146–157

Macfarlane, G.J., Bose, N. and Duffy, J.T., 2012, Marine Vessel Wave Wake:Focus on Vessel Operations within Sheltered Waterways. Submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy Australian Maritime College, University of Tasmania

Macfarlane, G.J., Bose, N. and Duffy, J.T., 2012, “Wave Wake: Focus on vessel operations within sheltered waterways”, To be presented at the SNAME Annual Meeting, Providence,, Rhode Island, 24-26th October 2012.

Patterson Britton and Partners. 2000. Progress report #5. Parramatta River long-term shoreline monitoring study, Waterways Authority of New South Wales

Repko, A., P. Van Gelder, H. G. Voortman, and J. K. Vrijling. 2005. “Bivariate Description of Offshore Wave Conditions with Physics-Based Extreme Value Statistics.” Applied Ocean Research 26 (3–4): 162–170.

Saha, Suranjana, Shrinivas Moorthi, Hua-Lu Pan, Xingren Wu, Jiande Wang, Sudhir Nadiga, Patrick Tripp, et al. 2010. “The NCEP Climate Forecast System Reanalysis.” Bulletin of the American Meteorological Society 91 (8): 1015–57. https://doi.org/10.1175/2010BAMS3001.1.

Sydney Institute of Marine Science (SIMS) 2014. Sydney Harbour Background Report 2014 Report prepared for NSW Department of Primary Industries by the Sydney Harbour Research Program at the Sydney Institute of Marine Science April 2014

Tromans, PS, and L Vanderschuren. 1995. “Response Based Design Conditions in the North Sea: Application of a New Method.” In . Proceedings of the 27th Offshore Technology Conference, Houston, pp. 387-397, OTC 7683. https://doi.org/10.4043/7683-MS.

Van der Westhuysen, André J., Marcel Zijlema, and Jurjen A. Battjes. 2007. “Nonlinear Saturation-Based Whitecapping Dissipation in SWAN for Deep and Shallow Water.” Coastal Engineering 54 (2): 151–70. https://doi.org/10.1016/j.coastaleng.2006.08.006.

Weatherall, Pauline, K. M. Marks, Martin Jakobsson, Thierry Schmitt, Shin Tani, Jan Erik Arndt, Marzia Rovere, Dale Chayes, Vicki Ferrini, and Rochelle Wigley. 2015. “A New Digital Bathymetric Model of the World’s Oceans.” Earth and Space Science 2 (8): 2015EA000107. https://doi.org/10.1002/2015EA000107.

Webb McKeown & Assoc. 2007. Parramatta River Estuary Draft Data Compilation Study. Prepared for Parramatta City Council, August 2007: pp. 34.

Wiegel, R.L., 1960, "Transmission of Waves past a Rigid Vertical Thin Barrier",Journal Waterways and Harbours Division, ASCE, Vol. 86, No. WW1, pp.1-12.

Winterstein, S. R., T. C. Ude, C. A. Cornell, P. Bjerager, and S. Haver. 1993. “Environmental Parameters for Extreme Response: Inverse FORM with Omission Factors.” In Proc., ICOSSAR-93, Innsbruck. http://www.rms-group.org/RMS_Papers/pdf/Todd/innsbruck.pdf.

Ziyu Xiao, Xiao Hua Wang, M. Roughan and D. Harrison 2019.Numerical modelling of the Sydney Harbour Estuary, New South Wales: Lateral circulation and asymmetric vertical mixing. Estuarine, Coastal and Shelf Science Volume 217, 5 February 2019, Pages 132-147