Port Hedland Spoilbank Marina

Metocean Design Criteria and Coastal Process Studies

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A	30-Aug-2019	Draft	Issued to client for progress review.	RW / SG	JC	SG
B	28-Oct-2019	Draft	Progress Reporting	SG	DRT	JC
C	5-Nov-2019	Draft	Progress Reporting with client comments on Rev A report addressed	SG	JC	SG
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Executive Summary

Baird Australia (Baird) were engaged to complete a coastal processes assessment for a proposed marina development on the Spoilbank at Port Hedland on behalf of the Department of Transport (DoT). This report provides a summary of the study tasks, including data analyses, impacts assessment of marina development on hydrodynamics and waves, derivation of site specific metocean design criteria and sediment transport modelling.

The proposed site is located at the southwest corner of the Port Hedland Spoilbank, adjacent to the existing Port Hedland Yacht Club. The design options for the marina facility were developed by the DoT and were subsequently refined by the design engineers, M P Rogers and Associates (MRA), a marine engineering specialist appointed by the DoT. Three marina layouts and two entrance channel alignments have been assessed.

A range of measured data and historical information has informed the development of numerical models to assess hydrodynamics (water levels, currents) and wave conditions for each of the developed options. The analysis has been completed for typical conditions in summer and winter season months and for both ambient and cyclonic conditions.

Baird re-established and refined a suite of existing numerical models for this study. A comprehensive model validation exercise was then completed to establish a degree of confidence in the modelling performance and identify potential biases to its application to design and ongoing management of the Spoilbank Marina facilities. Hydrodynamic and wave modelling was then completed for ambient and cyclonic conditions to quantify potential changes to hydrodynamic and wave conditions in the vicinity of the project.

In general, the marina concepts that were assessed will cause only local changes to the hydrodynamic and wave regime on the western side of the Spoilbank. However, the following is noted and should be considered during detailed design:

- under both ambient and cyclonic conditions, increases in metocean conditions (currents and waves) are predicted with a concentration of flows and waves on the head of the northern entrance breakwater.
- peak storm water levels including wave setup, would generate inundation past the extent of the proposed revetment along the northern edge of the marina development, assuming existing Spoilbank levels north of the marina are maintained.
- Wave propagation to the marina location is significantly influenced by the flat, shallow seabed and the presence of dredged channels (including the marina entrance channel). Modelling of post-development cyclonic wave conditions identified that Channel Option 2 affords greater protection of the marina entrance than Channel Option 1.

A comprehensive metocean design criteria study has been completed, applying a design storm approach to derive cyclonic design conditions at recurrence intervals of 1, 5, 20, 100, and 500-years. Design events were identified as representative of the 20, 100 and 500-years recurrence interval conditions, through analysis of Baird's Australian Tropical Cyclone Database, equivalent to a 10,000-year period, that includes a total of approximately 120,000 synthetic events across the Australian cyclone region with 28,096 synthetic events that track within 200km of the coast of the Australian mainland in the northern West Australian region. Assessments of hydrodynamic and waves post-development has also been completed.

A summary of the sediment transport pathways around the site has been completed based on review of previous studies. A prediction of the future shoreline evolution has been determined based on analysis of 30 years of satellite imagery. Modelled longshore transport rates under ambient and cyclonic events has been completed utilising available measured data and validated hydrodynamic and wave models. Both

siltation of the marina basin and sedimentation of the entrance channel have been investigated with a full process model and the outcomes presented as an annualised estimate of deposition.

The key findings from the sediment transport study are summarised as follows:

- The Spoilbank has been in a clear erosional trend from around 2003 and with the absence of a sediment source to replenish Spoilbank, the mechanisms for continued rotation of the westerly shoreline and loss of the Spoilbank landmass is clear.
- Estimates of the Spoilbank evolution over a 50-year period predict a loss of over 50% of its footprint as the erosional trend continues.
- An annualised longshore transport rate of between 40,000 and 50,000m^3/yr may be expected but will vary depending on the severity and frequency of tropical cyclone events. As such the range of longshore sediment transport in any given year could reasonably be between 15,000 and >100,000m^3.
- Bypassing of the northern breakwater will occur and depending on the structure/channel configuration selected, up to 24% of the longshore transport could bypass the structure and deposit in the entrance channel. The hook breakwater or siltation trap configurations reduce this bypassing potential by up to 2/3. However, the bypassing potential is significantly increased if the capacity of the sediment trap is not maintained.
- Deposition rates in the entrance channel are estimated to be between 0.5 and 3m annually, dependent of the occurrence and severity of tropical cyclones in a given year. For the outer channel section, a deposition rate in the range 0.2 to 0.5m per year is predicted based on the modelling.
- A background deposition of fine sediments will continually occur resulting in up to 0.25m of deposition (local) due to background concentrations of suspended sediments in the area.

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1. Introduction

Baird Australia (Baird) has been engaged by the Department of Transport to provide coastal processes, metocean design criteria and coastal engineering input to the Port Hedland Spoilbank Marina (SBM) project under contract number DOT404017c050 (Purchase Order 620061). This report presents details of study inputs, methodologies and outcomes of the investigations.

Note that this version of the report is an interim deliverable that will be updated as the study scope progresses.

The objective of the contracted scope of work was for Baird to:

- Provide expert advice on local coastal processes that will support design of the Spoil Bank Marina facility, including layout and metocean design criteria;
- Assess maintenance dredging requirements for the facility; and
- Evaluate anticipated and potential dynamics of the Spoil Bank, to identify and characterise options for longer-term coastal adaptation of the Spoil Bank precinct.

The scope is being undertaken based on the following tasks:

1. Data Review and Analysis
2. Entrance Design Workshop
3. Hydrodynamic and Wave Modelling
4. Metocean Design Criteria
5. Sediment Dynamics

1.1 Spoilbank Marina Development

In recent years the Town of Port Hedland, together with LandCorp and the Pilbara Development Commission, have been progressing planning for the development of a marina within Port Hedland. Following multiple iterations of the Port Hedland marina precinct concept the project received state government endorsement in 2018. A concept design was developed for a location on the western side of the Spoil Bank, adjacent to the Port Hedland Yacht Club, incorporating 2 lanes of boat ramp and 20 boat pens. Several supporting studies, including preliminary environmental assessment, have been undertaken based on this initial concept, as presented in Figure 1.1.

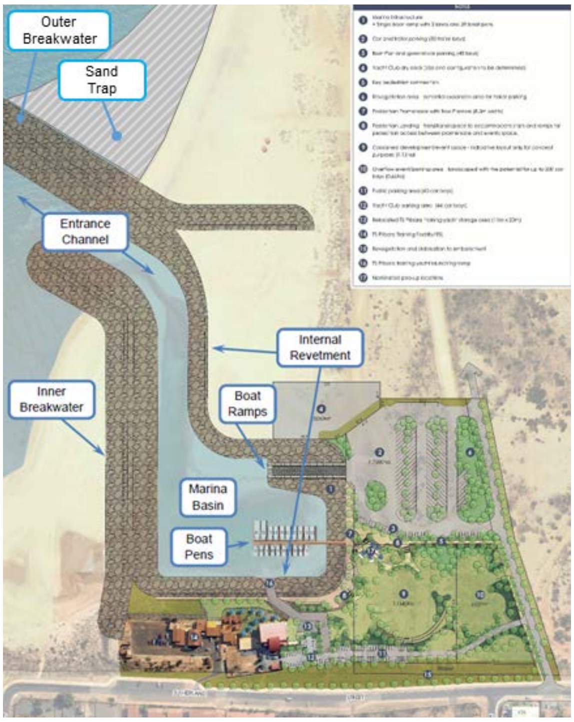


Figure 1.1: Initial Concept Layout plan for proposed Spoilbank Marina (TBB, June 2018)

1.2 Concept Design

The current project, co-ordinated by Department of Transport (DoT), is focused on design development of marine facilities for the Spoilbank Marina project. The coastal process study is one of several parallel investigations required to refine the concept design layout and specification.

1.2.1 Design Workshop

In June 2019, the DoT hosted an entrance design workshop, which was aimed at discussing and refining the marina concept layout to reduce the potential need for costly retrofitting and maintenance. During the workshop several items were discussed relating to the entrance configuration, and most importantly options to reduce the potential for sedimentation of the marina entrance channel and to minimise capital dredging works associated with the channel and marina basin. The DoT took the discussions on-board and further developed concept layout options for consideration in ongoing design and environmental assessments which were subsequently refined by the design engineers, M P Rogers and Associates (MRA). The three concepts that have been assessed in this report are presented in Figure 1.2.

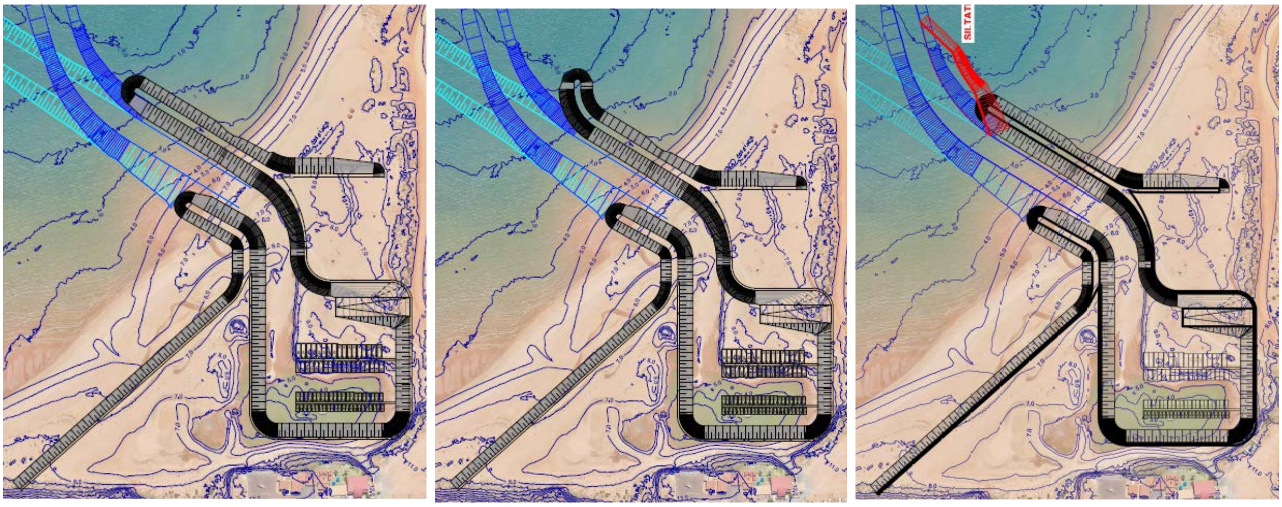


Figure 1.2: Spoilbank Marina Concept Layout Options. Left: Base Case, Centre: Option 1 (Breakwater Hook Design), Right: Option 2 (Base Case with Siltation Trap)

1.2.2 Marina Basin and Revetments

The marina concept (Figure 1.2) includes a basin of approximately 160 x 170m in dimension that will accommodate up to 80 vessels of sizes between 10 and 20m in length. A dual boat ramp is located in the north eastern corner with a fairway that runs along the northern extent of the basin to connect with the marina entrance channel. The marina basin will be contained by rock revetments on all sides with additional external revetments constructed to provide long term reclamations of the northern and western landside areas. These are required due the highly mobile and evolving nature of the Spoilbank land mass.

The northern and southern training walls are 200m and 75m in length (along the crest), respectively and will act to stabilise the entrance, provide protection from incident waves and act as sediment traps to inhibit nearshore sediment transport from infilling the entrance channel. The Option 1 layout includes a breakwater hook feature at the end of the northern training wall where most of the sediment bypass is expected to occur, to attempt to keep sedimentation away from the entrance channel.

1.2.3 Entrance Channel

The entrance channel starts from the marina basin in a north-south alignment before turning to a north westerly orientation through the entrance. It is protected through the shoreline and intertidal areas by two entrance training walls (Figure 1.2).

Offshore there are two entrance channel alignments that are being considered, as presented in Figure 1.3. The channels are between 900 and 1000m in length and extend out to design depth on a final heading east-north east parallel the main Port Hedland shipping channel (Goldsworthy channel) so as to encourage separation of commercial and recreational vessels. The entrance channel is 30m wide (at the channel toe) and will be maintained to -2mCD (note, channel will be dredged to -2.5mCD including 0.5m over-dredge for sedimentation allowance) to provide all tide access to all vessel sizes in the proposed marina fleet. The two entrance channel alignments will be assessed based on capital dredging requirements, navigational safety and maintenance requirements (i.e. sedimentation rates).

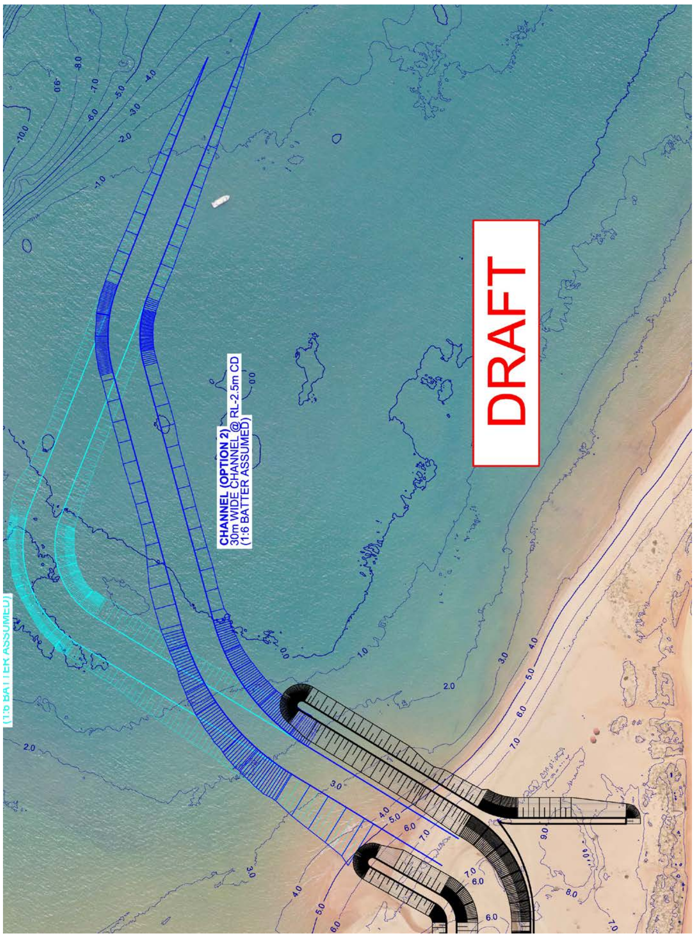


Figure 1.3: Entrance Channel Alignment Options. Option1 in Light Blue, Option 2 in Dark Blue.

2. Metocean Climate

Port Hedland is located of the Northwest Shelf (NWS) of Australia approximately 190km East-Northeast of Karratha and 460km Southwest of Broome, as shown in Figure 2.1. The metocean climate has strong seasonality of winds and waves, however is generally characterised by its macrotidal, semi-diurnal tides and low ambient wave climate. Being at a latitude of -20.3 degrees, the region is subject to the Australian monsoon during the summer months (November through April) characterised by high rainfall and tropical cyclones, with three events per year, on average, influencing the metocean conditions at Port Hedland.

The proposed marina is located at the southwestern corner of the Port Hedland Spoilbank, an artificial mobile landform, that is located on the eastern side of the main Goldsworthy shipping channel just outside of the Port Hedland Inner Harbour. This site provides a relatively sheltered position from offshore conditions, between the Port Hedland Spoilbank landform and the Goldsworthy shipping channel, with the nearshore area consisting of naturally shallow, relatively flat, seabed conditions.

Figure 2.1: Locality Map of the proposed Port Hedland Spoilbank Marina

Metocean data, collected by the Pilbara Port Authority (PPA), Bureau of Meteorology (BoM) and DoT, was made available for this project and provides a description of the site specific metocean conditions. Metocean parameters for water levels, waves, currents and winds over a 19-week period (approx.) between December 2018 and April 2019, were provided across 10 locations, including:

- Port Beacon C2 (PPA) – Waves (DWR)
- Port Beacon 15 (PPA) – Waves (DWR)
- Port Beacon 16 (PPA) – Waves, Currents (AWAC), Winds (Met Station)
- Port Beacon 17 (PPA) – Water Level (Tide Gauge)
- Port Beacon 31 (PPA) - Water Level (Tide Gauge)
- Port Beacon 47 (PPA) – Waves, Current (AWAC), Water Level (Tide Gauge)
- Port Hedland Tower (PPA) – Wind (Met Station)

- HD01 (DoT) – Waves, Water Level, Currents (AWAC)
- HD02 (DoT) – Waves, Water Level, Currents (AWAC)
- Port Hedland Airport (BoM) – Wind (Met Station)

The locations of the metocean measurements is presented in Figure 2.2.

Baird have completed a review of the data available over the full duration of the datasets. Timeseries plots of key parameters from the PPA and DoT datasets, including wave, water level and current parameters, are included in Appendix A for the full deployment period of each dataset.

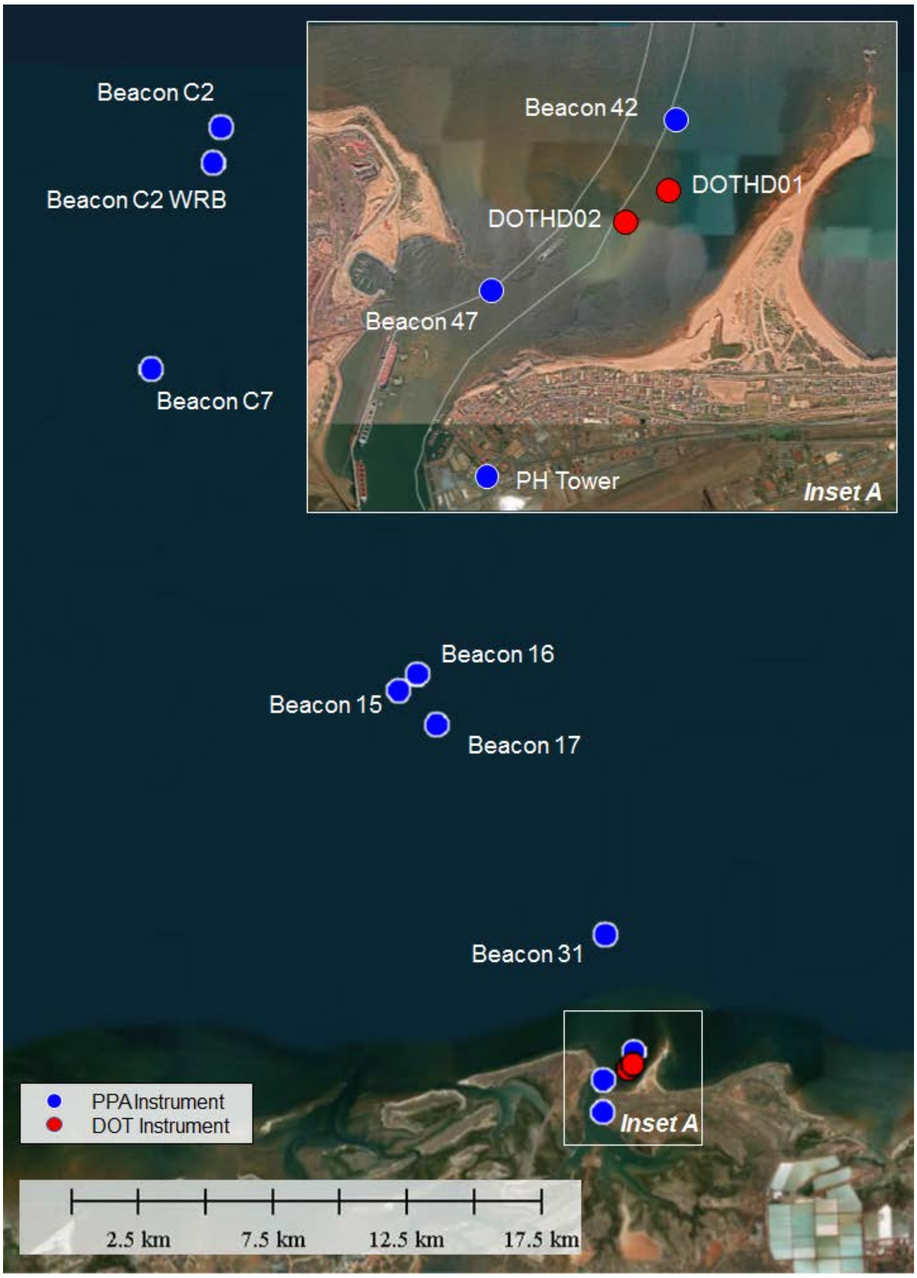


Figure 2.2: Location of Metocean Measurements from PPA and DoT

2.1 Tropical Cyclones

The Pilbara coastline is the most cyclone-prone region of the Australian mainland, with the area immediately surrounding Port Hedland having the highest frequency of Category 4 and 5 cyclones that make landfall. Approximately 3 cyclones per year, on average, influence the metocean conditions at Port Hedland. Events of this magnitude govern the design criteria for engineering works in the Port Hedland region, including design wave heights and water levels.

2.2 Water Levels

The Port Hedland region is a macro-tidal environment and is subject to large, semi-diurnal tides which drive water level variations over an approximate two-week spring-neap cycle. Tidal ranges vary between 2m during neap tides up to 7.5m during very large spring periods. A summary of tidal planes at Port Hedland is provided in Table 2.1.

Table 2.1: Port Hedland Tidal Planes (DoT, 2019)

Tidal Plane		Level (m LAT - 2005)	Level (m AHD)
HAT	Highest Astronomical Tide	7.61	3.72
MHWS	Mean High Water Springs	6.73	2.84
MHWN	Mean High Water Neaps	4.67	0.78
MSL	Mean Sea Level	4.00	0.11
MLWN	Mean Low Water Neaps	3.33	-0.56
MLWS	Mean Low Water Springs	1.27	-2.62
LAT	Lowest Astronomic Tide	0.07	-3.82

In addition to tides, mean water levels in the region are influenced by a range of other processes, including oceanographic currents, low pressure systems and inter-annual variability associated with the El Niño–Southern Oscillation, resulting in residuals in the range of +/-0.2m, typically (Cardno, 2011). However, the largest amplitude contributor to water level residuals is storm surge which can accompany tropical cyclone events and increase the total water level by over 1m above highest astronomical tide (HAT).

2.3 Winds

Wind conditions at Port Hedland are seasonal with clear differences in the prevailing winds during the Summer and Winter months. North-westerly winds generally blow during the Summer Monsoon followed by strong easterlies/south-easterlies over winter months before a gradual return to north-westerly conditions in spring. These general trends are reinforced by land and sea breezes induced by temperature differences between land and water. Figure 2.3 presents the seasonal wind roses from the Port Hedland Airport that clearly identifies the seasonal differences in the wind climate.

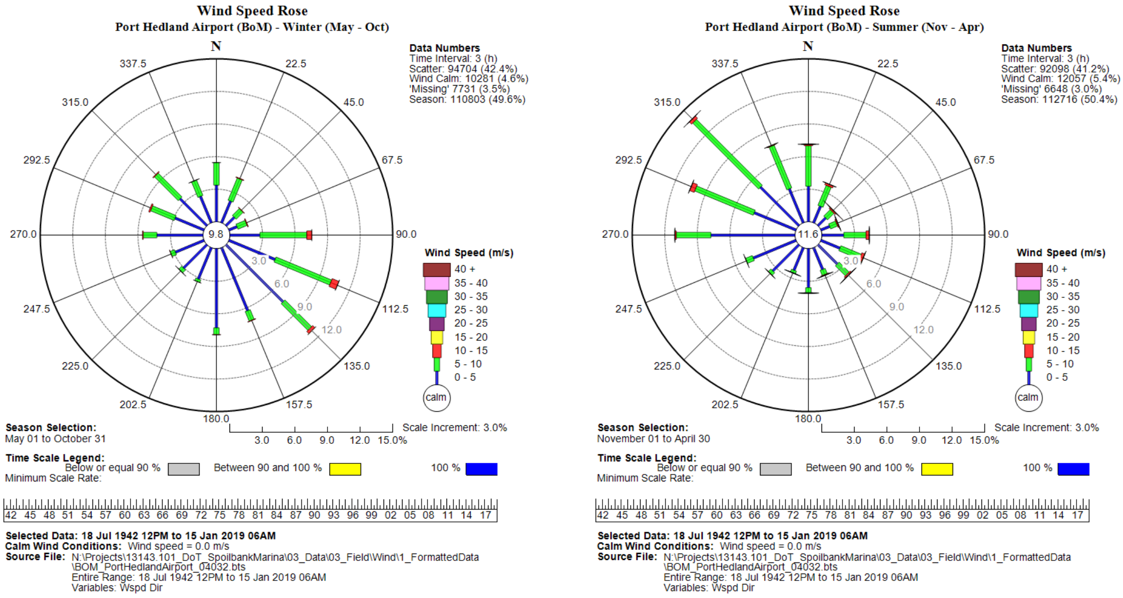


Figure 2.3: Wind Speed Roses at the Port Hedland Airport Station (BoM) for Winter months (left) and Summer months (right). Analysis of BoM data from 1942 to 2019.

2.4 Currents

Due to the large tidal range which is present at Port Hedland and the large tidal prism which exists inside the Inner Harbour, peak tidal currents within the harbour can reach velocities in excess of 1.5 knots, with maximum velocities in the narrowest part of the Harbour near Hunt Point exceeding 2.5 knots (depth-averaged) on occasion. The tidal flow patterns outside and within the Inner Harbour are extremely complex, due to the large range in depths and the storage within the multitude of creeks which can extend several kilometres inland.

Current flows past the SBM site are tidally dominated and heavily influenced by the presence of the Goldsworthy Channel that acts as the main conveyance of flow in and out of the Port Hedland Inner Harbour. As a result, there is a strong tidal inequality between flood and ebb tide flows, with markedly stronger flows associated with a flood tide, due to the fact that the majority of ebb tide flow is constrained to the channel, particularly at lower tide levels. Figure 2.4 presents current speed roses from measured data at the DoT AWAC locations (DoTHD01 and DoTHD02). Peak flood tide currents speeds of up to 0.6m/s are observed, with peak current speeds of 0.8m/s measured under TC Veronica, as a result of residual currents generated by winds in the order of 0.1 – 0.2m/s as shown in Figure 2.5.

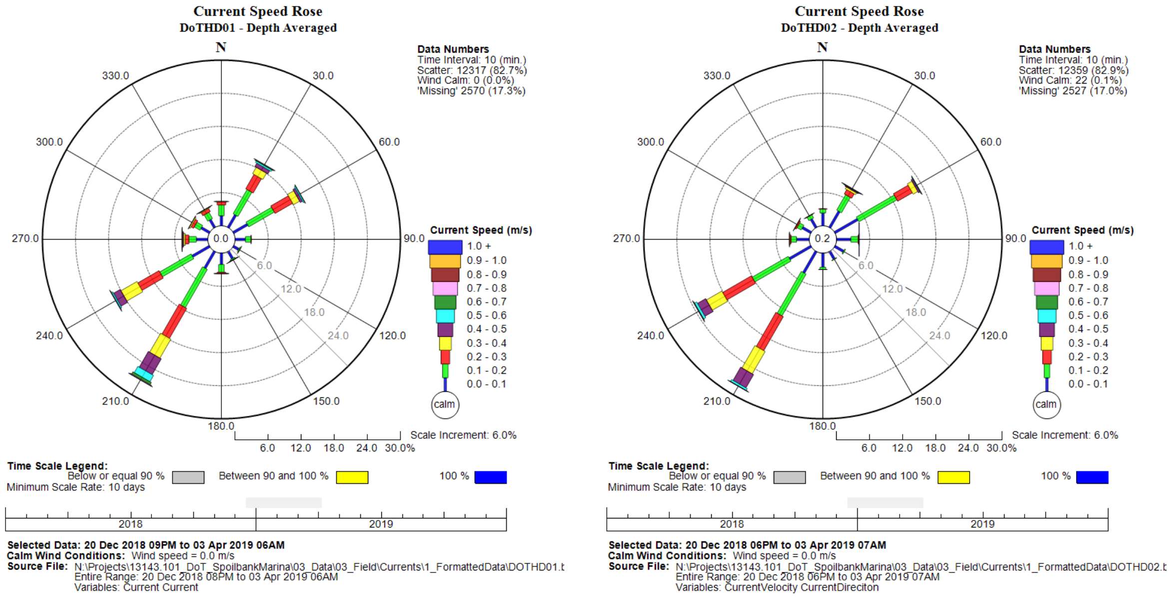


Figure 2.4: Current Speed Roses at the DoTHD01 (left) and DotHD02 (right) AWAC Locations. Direction convention is shown as 'Direction Going to'.

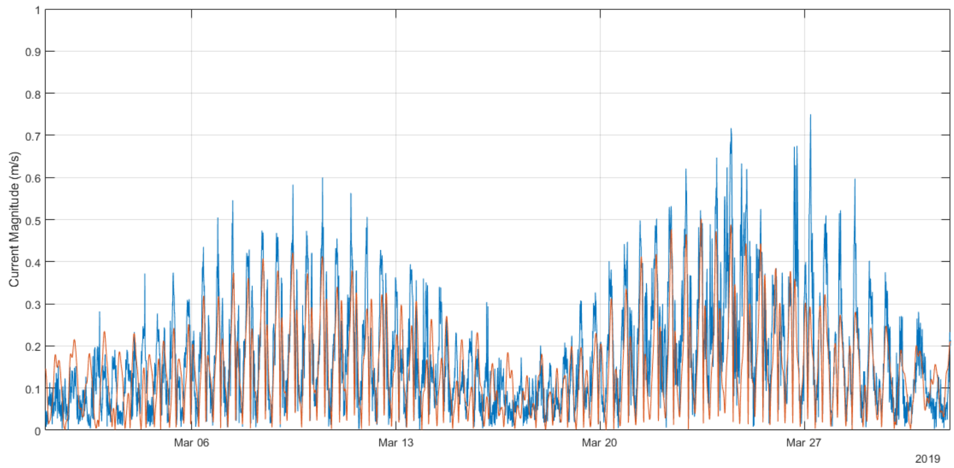


Figure 2.5: Timeseries plot of Measured (blue) and tidal (red) Current Magnitude at location DoTHD02.

2.5 Waves

The ambient wave climate at Port Hedland is largely described by a persistent north-westerly swell which propagates long distances to the Pilbara coast from the Indian Ocean. These swell waves generally arrive with peak periods of 12 to 18 seconds and are most prevalent during the winter months, though present throughout the entire year. Due to the broad shelf offshore of Port Hedland, swell at the entrance to Port Hedland is normally negligible (Hs<0.1m) and even 15 km offshore, at the Beacon 15/16 wave measurement locations, swell heights (Hs) are normally less than 0.3m.

Locally generated sea waves are also prevalent from the north-west quadrant throughout the year with peak periods of 2 to 9 seconds, typically. These shorter period waves can be comparatively energetic with offshore significant wave heights in excess of 2m during the monsoonal months due to the frequent passage of tropical lows and occasional extreme cyclonic events. During the period from October to April each year, strong westerly sea breezes develop along the coastal waters of the Pilbara which are frequently 15 to 20 kts and can generate westerly seas of 1 to 1.5m (Hs). Wave penetration to the SBM entrance is limited by seabed features such as the Spoilbank land mass and Goldsworthy shipping channel.

Figure 2.6 presents the wave height roses for the DoT AWAC locations. Measured data at the DoT AWAC locations, collected over a 3-month period during the Wet season, indicate that wave conditions are below 1m (Hs) approximately 98% of the time, with wave conditions only exceeding 1m (Hs) during TC Veronica between the 22nd and 26th of March 2019. Ambient wave conditions approach the measurement locations from an almost exclusively North-northwest direction, however notably the larger wave heights during TC Veronica propagate from the North, as demonstrated by the wave height intensity rose in Figure 2.7. Winds during the Dry season (winter) months are typically easterly, a direction from which the SBM location is protected due to the presence of the Spoilbank and as such the wave climate is reduced with wave conditions below 0.5m (Hs) approximately 98% of the time.

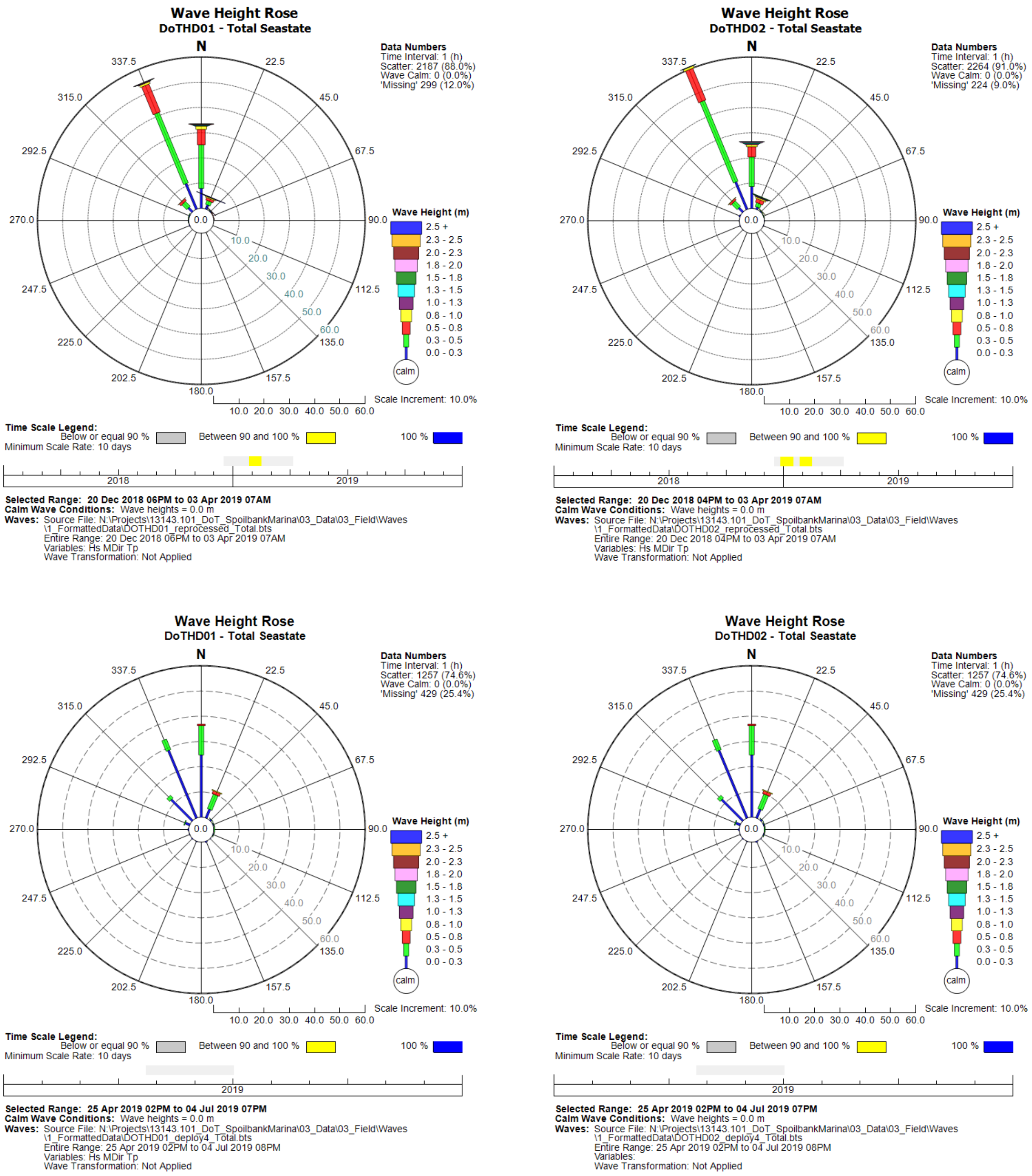


Figure 2.6: Wave Height Roses at the DoTHD01 (left) and DotHD02 (right) AWAC Locations for Summer (top) and Winter (bottom) deployments.

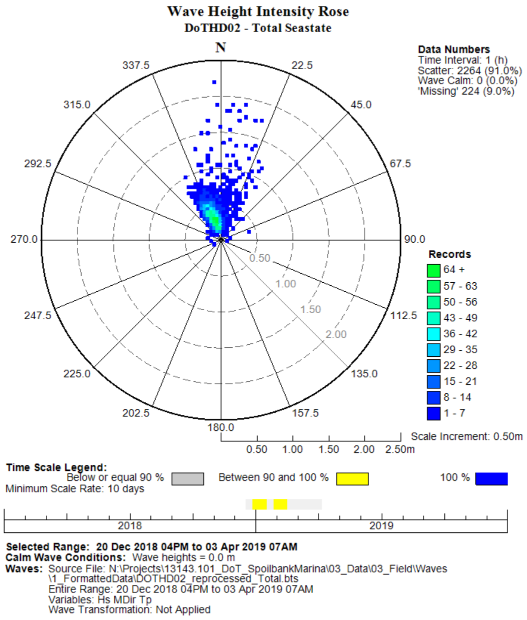


Figure 2.7: Wave Height Intensity Rose at the DoTHD02 AWAC Location.

2.5.1 Waves in Shallow Water

The nearshore shallow water measurements by the DoT captured wave conditions under TC Veronica (March 2019). This provided a unique dataset of direct relevance to nearshore shallow water cyclonic wave conditions at the entrance to the Spoilbank Marina. Following initial review by Baird and reprocessing of the data by DoT, a reliable dataset of measured wave parameters was received that included significant and maximum wave heights along with concurrent water level data. Limiting wave conditions in nearshore areas are typically defined by a wave height on depth ratio, which is known to be dependent on nearshore slope, however limited definitive guidance is available for very flat shallow areas as observed in the vicinity of the SBM.

Analysis of the DoT AWAC data was carried out and wave height on depth ratios calculated for all available records over the measurement period. The timeseries of wave height, water level and wave height on depth are provided for significant wave height (Hs) in Figure 2.8 and for maximum wave height (Hmax) in Figure 2.9 for the DoTHD01 location. Plots for DoTHD02 are provided in Appendix A and are consistent with the Figures below.

The presentations demonstrate that under ambient Wet season conditions, dominated by north westerly sea breeze conditions, waves are typically below 1m (Hs) and wave height on depth ratios (Hs/d) are below 0.2. However, for wave conditions above 1m (Hs), as observed during TC Veronica (March 2019), the ratio peaks at 0.33.

At the DoT AWAC locations, wave conditions are known to be affected by the available water depth as there are clear tidal signals in the measured wave height data record. While it is unlikely that depth limited breaking is induced at these depths, the wide, flat and shallow nearshore area results in a large amount of wave dissipation, thereby limiting potential wave heights at the SBM. Based on the measured maximum wave height on depth ratios presented in Figure 2.9, limiting wave height on depth ratios under cyclonic conditions of 0.4 (Hs) and 0.65 (Hmax) are considered appropriate for this location.

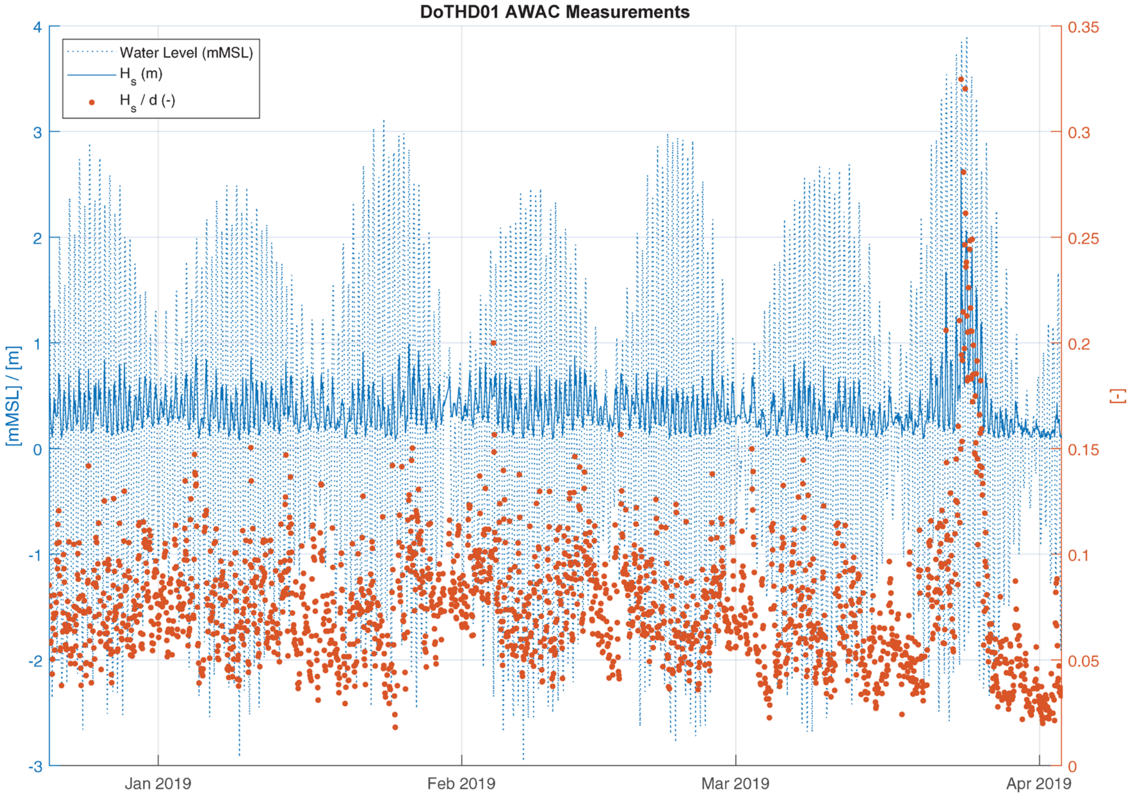


Figure 2.8: Timeseries of water level (measured), significant wave height (measured) and wave height on depth (derived) from observations at DoTHD01.

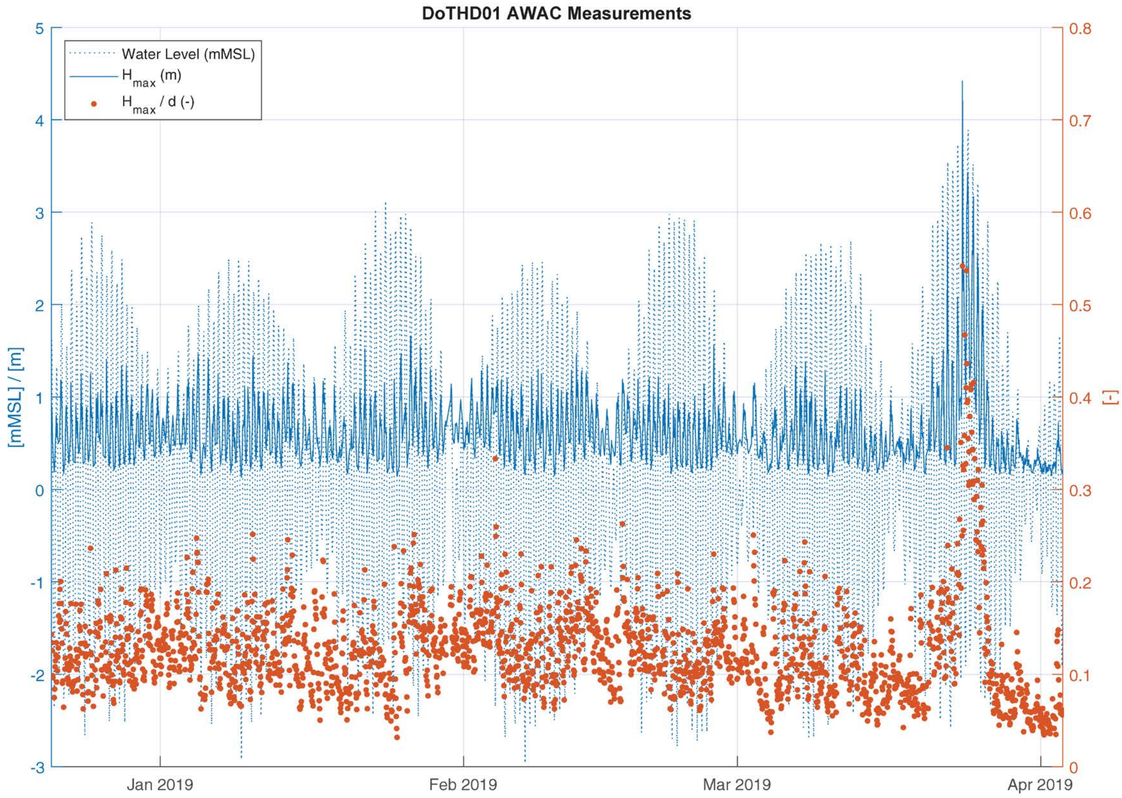


Figure 2.9: Timeseries of water level (measured), maximum wave height (measured) and wave height on depth (derived) from observations at DoTHD01.

2.5.2 Maximum Wave Height

The design criteria defined in Section 4, includes an estimate of the maximum wave height at each return period. This estimate requires an assumption of the Hmax to Hs ratio. In deepwater, assuming a Rayleigh distributed seastate, the maximum wave height ratio generally follows a relationship that is dependent on the wave period, or number of waves over a given duration. However, in shallow water the maximum wave height of the seastate may be truncated due to shallow water dissipation and depth-limited breaking. The measured records at the DoT AWAC locations were therefore analysed to understand the range and randomness of the observed maximum wave heights. Figure 2.10 presents a Cumulative Distribution Function (CDF) of the maximum wave height ratio (Hmax / Hs) for all records from both AWAC locations. The CDF indicates a relatively narrow range of between 1.6 and 1.8 with a mode of 1.67. Further interrogation of the dataset for wave conditions equal to or greater than 1m (Hs) indicates a very consistent Hmax ratio of 1.66 to 1.68. As a result, an Hmax to Hs ratio of 1.7 is considered appropriate for design purposes at the Spoilbank and has been adopted in the development of metocean design criteria.

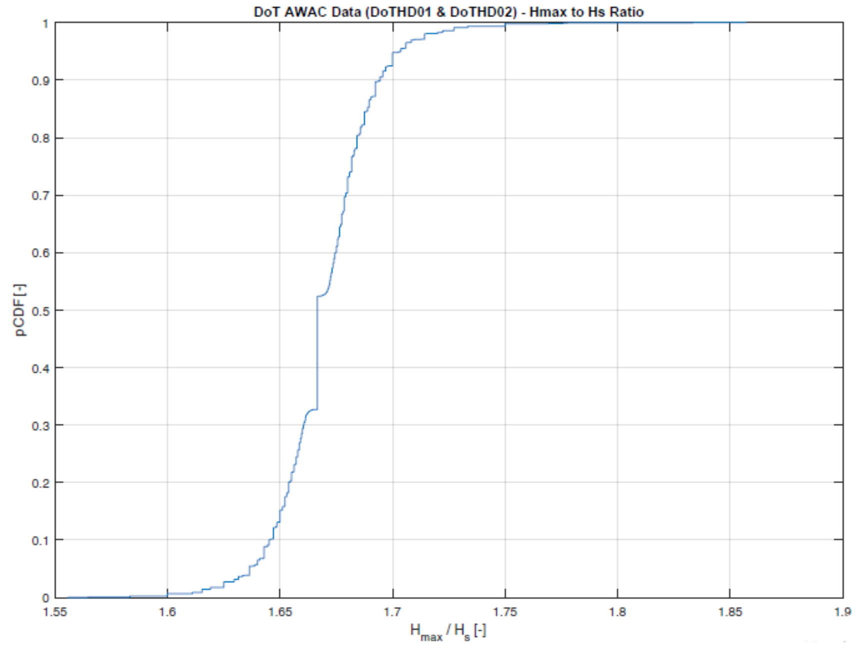


Figure 2.10: CDF of Maximum Wave Height Ratio (Hmax/Hs) from measured data at the DoT AWAC locations (DoTHD01 & DotHD02).

2.6 Representative Seasonal Months

For the purposes of model analyses of the various SBM design options, representative wet and dry season months were identified. With hydrodynamic conditions at the SBM location dominated by the macrotidal regime, and hence relatively consistent from month to month, representative seasonal months have been identified based on available offshore measured wave data at Beacon 15/16 with consideration of both sea and swell conditions. This ensures that the selected months are representative of the seasonal wind climate (sea conditions) and swell climate.

Baird sourced additional directional wave data from Beacon 15/16 extending back to 2006, which was used to define the longer-term offshore wave climate at Port Hedland. Figure 2.11 presents the Dry and Wet season wave climates (total seastate) from available data at Beacon 15/16.

The selection of representative seasonal months as part of this coastal process assessment, is primarily focussed on sediment transport. As is discussed in Section 5.2, through comparison of bathymetric surveys and numerical modelling, the primary sediment transport process at this site is longshore sediment transport. This process is also shown to be predominantly driven by wave driven currents and occurs across a limited vertical section of the shoreline between +0.5 and +2mAHD. This makes the longshore transport regime relatively insensitive to seasonal changes in mean water level which are in the order of +/- 0.3m (Seashore, 2019).

As such, the selection of representative seasonal months has focussed on the wave climate (both sea and swell) with secondary consideration given to water levels. It is noted that at the shoreline, tidal currents are relatively low and hence not of primary concern for the consideration of longshore sediment transport. Further, it is demonstrated in Section 5.4 that sediment transport processes are dominated by episodic cyclone events, where the 1-year ARI cyclone event generates more transport than the annual ambient conditions (on average), which is not unexpected given the low exposure of the site to ambient wave conditions.

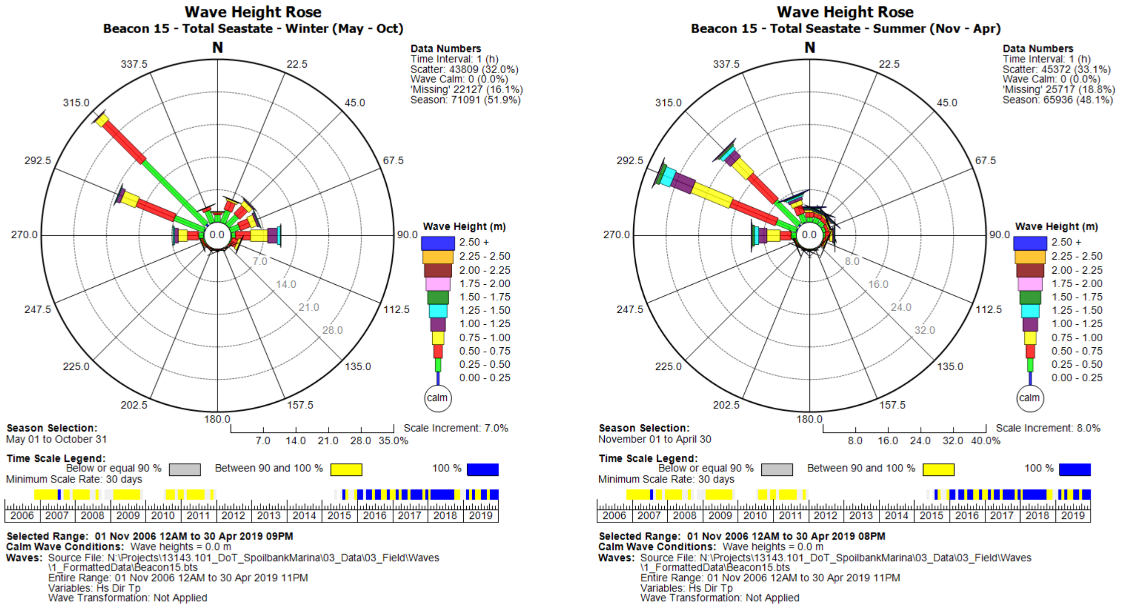


Figure 2.11: Wave Height Roses (Total Seastate) at Beacon 15/16 for available Dry (left) and Wet (right) Season Data.

The selected Dry and Wet season cases are as follows:

- Dry Season: the measured data indicated that the June 2016 period was most representative of winter swell conditions at Beacon 15/16. The predominance of Northwesterly swell conditions and swell wave height occurrence above 0.45m (Hs) was a good match the climatic average. See Figure 2.12 for a comparison of the wave height roses between all dry season data and June 2016 for swell conditions. The directionality and intensity of sea conditions was also representative of typical dry season conditions.

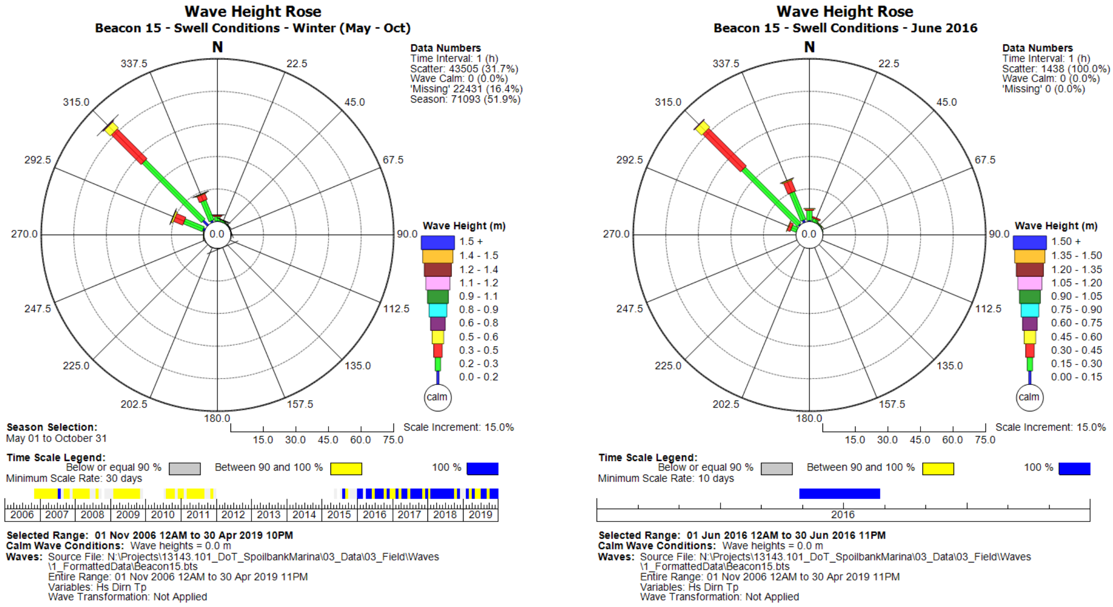


Figure 2.12: Swell Wave Height Roses at Beacon 15/16 for all Dry Season Data (left) and the Selected Representative Winter Month, June 2016 (right).

- Wet Season: the measured data indicated that January 2019 was most representative of summer sea conditions at Beacon 15/16. The exceedance of sea conditions up to 2m (Hs) was representative of the climatic average and the seasonally dominant West-Northwest to Northwest directions were also observed during January 2019. See Figure 2.13 for a comparison of the wave height roses between all Wet season data and January 2019 for sea conditions. Underlying swell conditions were also typical of summer months.

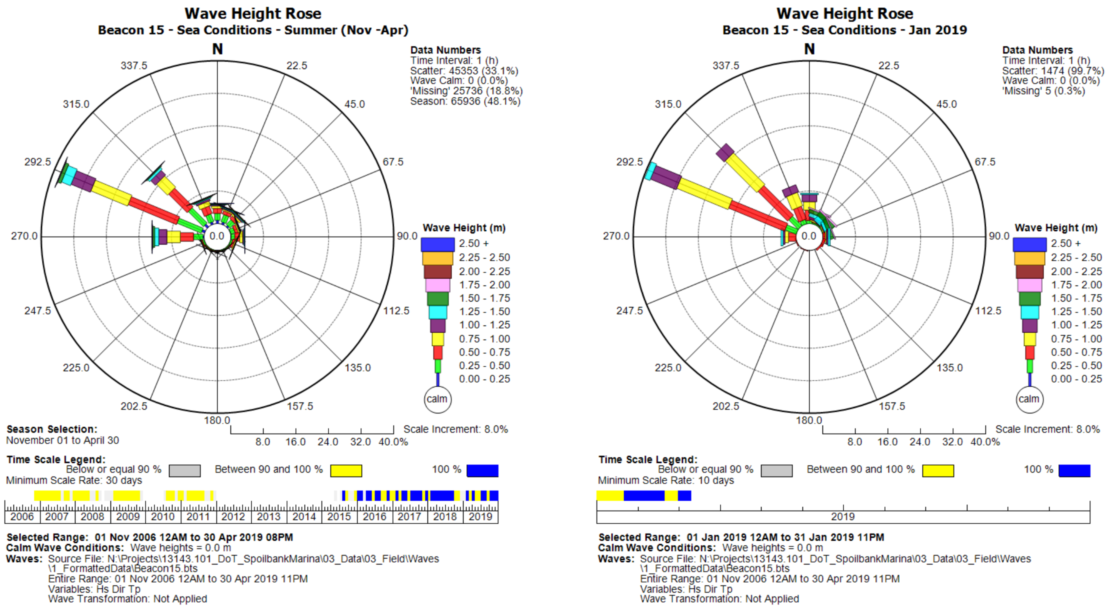


Figure 2.13: Sea Wave Height Roses at Beacon 15/16 for all Wet Season Data (left) and the Selected Representative Wet Season Month, January 2019 (right).

The representative Dry and Wet season months will be used for the modelled cases as part of the coastal processes and sediment transport assessments.

3. Hydrodynamic and Wave Modelling

Baird has re-established and refined a suite of existing numerical models for this study. A comprehensive model validation exercise was then completed to establish a degree of confidence in the model performance and identify potential biases to its application to design and ongoing management of the Spoilbank Marina facilities. The validated hydrodynamic and wave models were then applied to analyse ambient and cyclonic conditions for the SBM site to quantify potential changes to hydrodynamic and wave conditions associated with the design structures.

3.1 Model Systems and Validations

The following numerical models and datasets have been applied in the SBM investigations:

- Baird's Monte Carlo cyclone track model;
- Baird's Cyclone Windfield (CycWind) model;
- Shelf-scale Hydrodynamic model (Delft-FM);
- Shelf-scale Spectral Wave model (WW3);
- Local-scale Coupled Hydrodynamic and Spectral Wave model (Delft3D FWF); and
- Local-scale Phase Resolving (Bousinesq) Wave model (MIKE21-BW).

The various modelling components have previously been applied by Baird for a number of coastal processes and design criteria studies at coastal locations on the North West Shelf (NWS), including Port Hedland. The model setups and validation are presented in the sections below.

Validation of the numerical model systems and methods has focussed on hydrodynamic and wave conditions that were observed during a metocean data collection deployment completed by the DoT over a 19-week period (approx.), between December 2018 and April 2019. This included observations of TC Veronica, in March 2019, which has been used as a key event in the validation of models under extreme cyclonic conditions.

3.2 Monte Carlo Cyclone Event Model

To derive extreme metocean design conditions out to the 500-year ARI for the Port Hedland SBM project, a suitable cyclone event set that extends the historical record with simulated events using a stochastic-based modelling approach thereby capturing peak water level and wave conditions over a long period was required. Baird's Australian Tropical Cyclone Database, equivalent to a 10,000-year period, includes a total of approximately 120,000 synthetic events across the Australian cyclone region with 28,096 synthetic events that track within 200km of the coast of the Australian mainland in the northern West Australian region. Such approaches have been applied in the USA and Australian context for several years (Vickery et al 2000a, 2000b and James and Mason 1999).

Baird Australia's Monte Carlo cyclone track model covers the Australian cyclone region (90 °E to 160 °E, 10 °S to 40 °S) and is based on the Bureau of Meteorology historical best track database using cyclone tracks recorded in the post-satellite era (1960/61 to 2017/18 seasons). Figure 3.1 presents the cyclone tracks of historical tropical cyclones from 1960 to 2016 (262 events) that passed through the North-West Shelf region, alongside the generated Monte Carlo track dataset (47,206 events over 10,000 years).

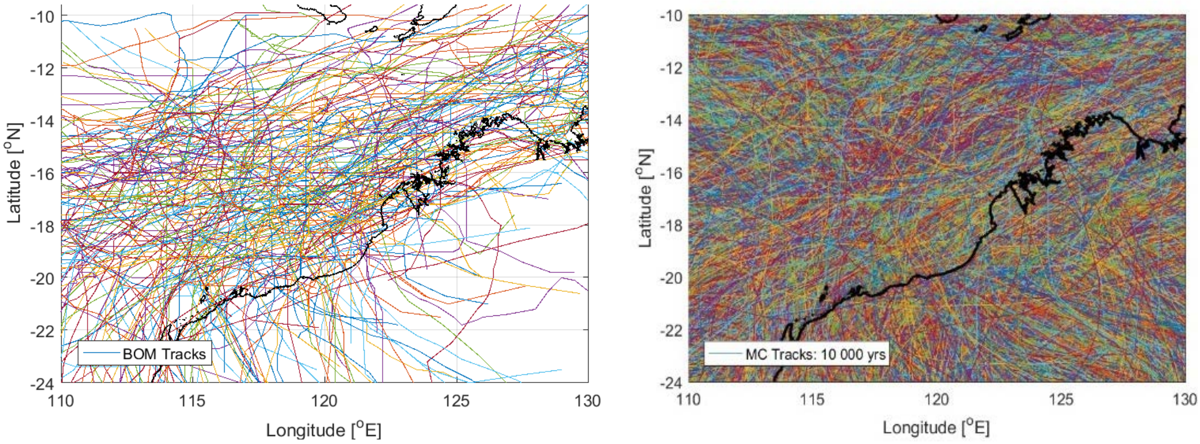


Figure 3.1: Tropical cyclone tracks crossing into the Indian Ocean model domain: (left) historical (1960 – 2016) and (right) Monte Carlo track dataset (10,000 years) for Northwest Western Australia.

Western Australia has a high exposure to tropical cyclone events, with an average of 5 cyclones occurring in the region per year, with 2 making landfall on average, and the potential for multiple landfalls owing to the geometry of the coastline (BoM, 2017). From the Monte Carlo event set, 28,096 events are observed to pass into the northern WA region and within 200km of the coast. The rate of occurrence and spatial distribution of the Monte Carlo event set compares well against the historical track dataset as presented in the Sections below.

3.2.1 Monte Carlo Cyclone Event Model Validation

The operation and validation of the synthetic cyclone track model has been presented in Baird Australia (2015 and 2016) and Burston et al (2015). The validation shows good agreement between the Monte Carlo model and the historical climatology over the northeast Indian Ocean (Figure 3.2). Further, the incidence of tropical cyclone landfall along Western Australia coastline in the Monte Carlo model verifies well against the historical climatology (Sectors 9-14 in Figure 3.3), which is important for metocean criteria development.

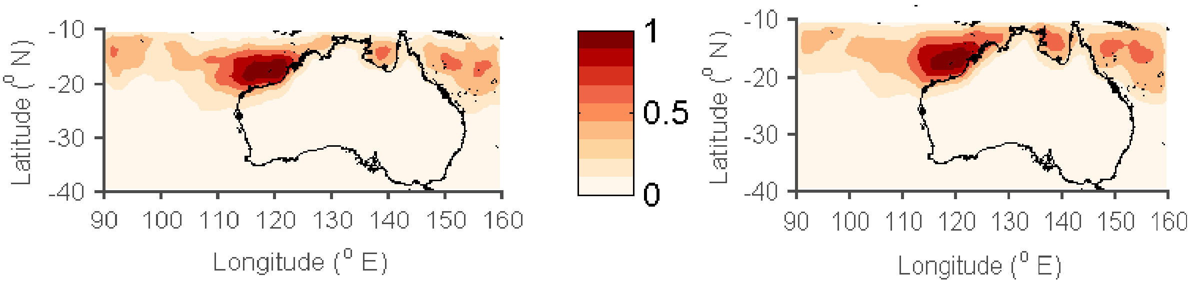


Figure 3.2: Comparison of Measured Annual Track Density (upper) and Modelled Mean Track Density (lower), derived from a 500 member ensemble, of tropical cyclones in the Australian region between 1961 to 2014.

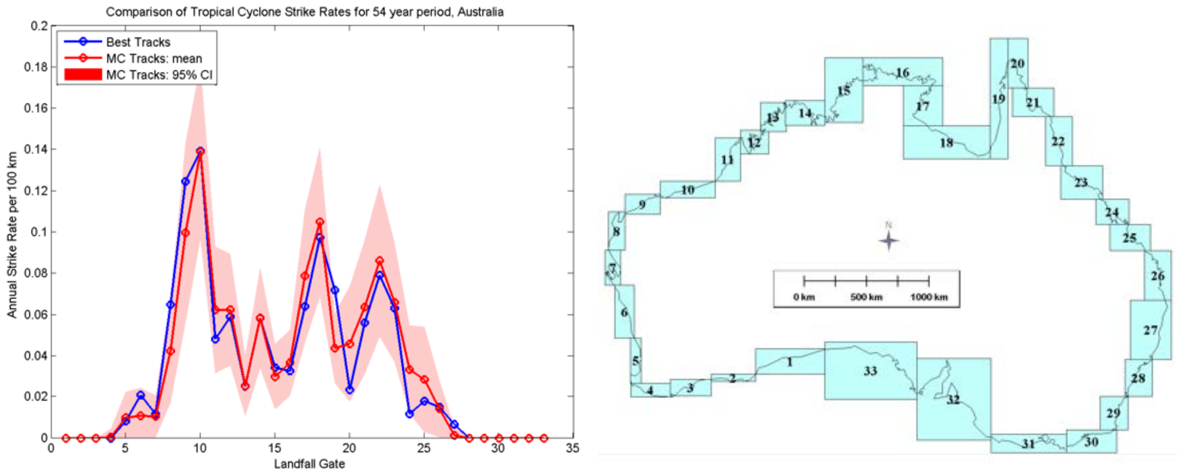


Figure 3.3: (Left) Comparison of landfall incidence along the Australian coastline: measured (blue) BOM best track dataset: 1960/61 – 2014/2015 and modelled (red) 500-member ensemble of the Monte Carlo track model for a corresponding time period. (Right) Landfall crossing 'gates'.

Further, the cyclone intensity in the Monte Carlo model, by measure of the central pressure, compares well to the historical event set. Figure 3.4 presents the cumulative distribution of central pressure for all track timesteps within the West Pilbara region (113 to 120ºE and 22 to 19ºS).

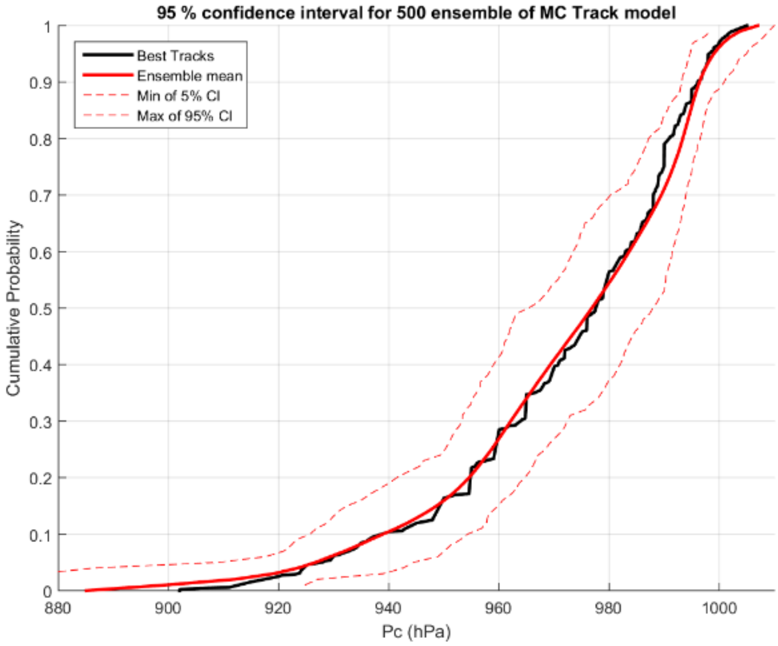


Figure 3.4: Comparison of the Cumulative Distribution of Cyclone Central Pressure within the West Pilbara region.

3.3 Cyclone Windfield Model

Cyclone wind and pressure forcing for hydrodynamic and wave modelling has been developed using Baird's in-house *Cycwind* program. The model combines a Holland et al. (2010) vortex model blended into regional scale atmospheric wind and pressure fields, such as those from the Climate Forecast System Reanalysis (CFSR) or ECMWF ERA5 Reanalysis datasets. The cyclone vortex is generated by applying cyclone parameters from the Bureau of Meteorology (BoM) best tracks or Monte Carlo cyclone track databases and allows for modification of track parameters (within reasonable bounds) to improve the fit against observed wind and pressure records.

Note that cyclone windfield blending with regional atmospheric fields was only completed for historical events, with events from the Monte Carlo track dataset run with a Holland et. al. (2010) vortex only. Sensitivity modelling of the validation case (presented below) was completed with and without blending with regional atmospheric fields and results for peak storm surge and wave height were found to be insensitive to their inclusion.

3.3.1 Cyclone Windfield Model Validation

The cyclone windfield model was validated against wind and pressure observations at 3 Bureau of Meteorology (BoM) sites during TC Veronica in March 2019, including Port Hedland, Barrow Island and Karratha. Validation plots and validation metrics for wind speed, direction and atmospheric pressure at Port Hedland are presented in Figure 3.5 and for other locations in Appendix B.

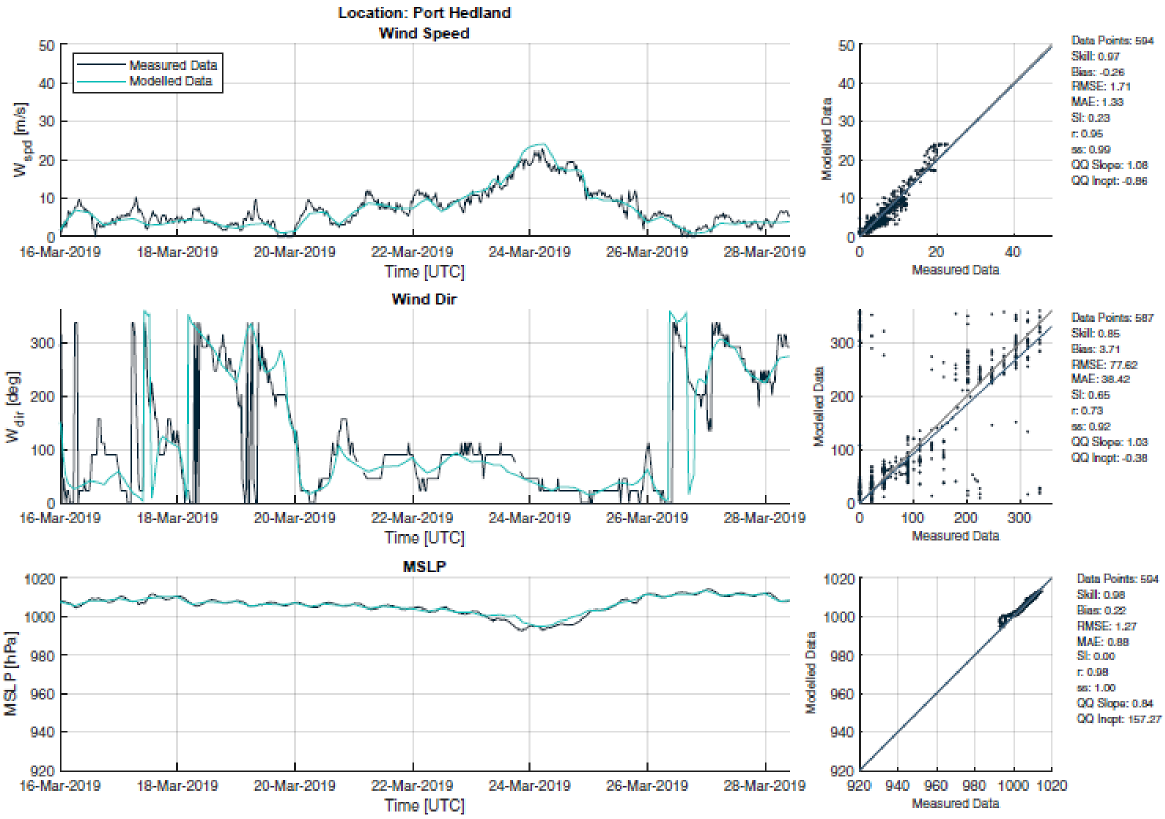


Figure 3.5: Cyclone Wind and Pressure field Validation at Port Hedland (BoM Airport Data)

Overall, model validation is good with model skill exceeding 95% and MAE and RMSE of less than 2 m/s for coastal locations including at Port Hedland. Figure 3.6 presents an example of the spatial wind and pressure field for TC Veronica near the time of peak intensity of the event.

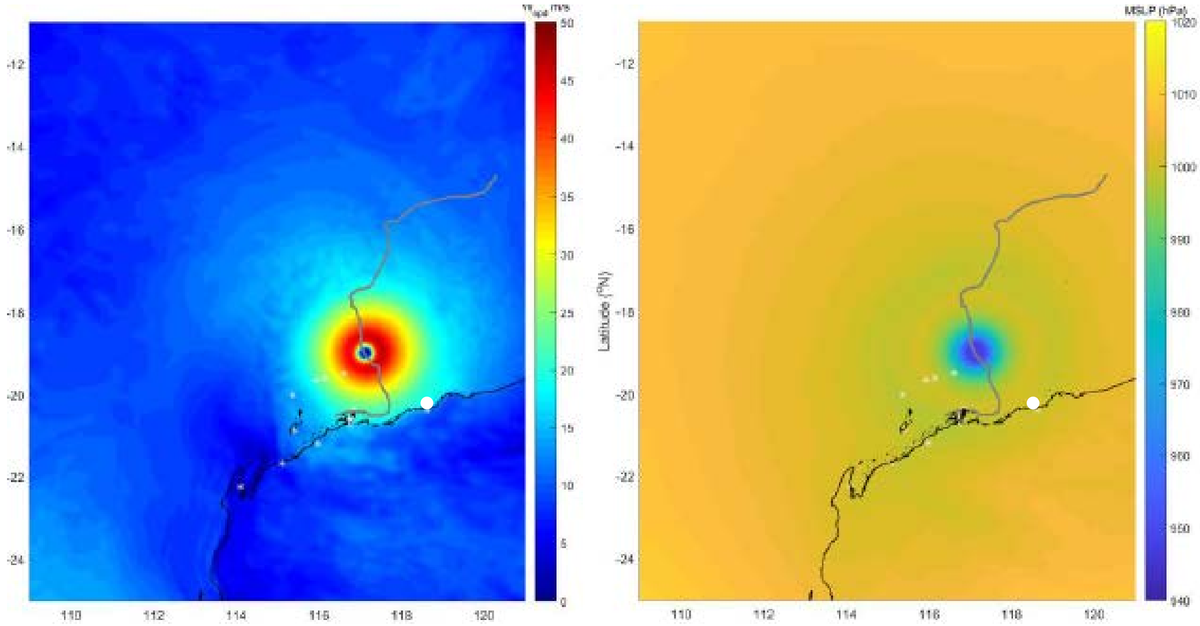


Figure 3.6: Hindcast wind speed (left) and surface atmospheric pressure (right): 06:00 23 March 2019 (UTC). Port Hedland is identified by the white dot.

3.4 Regional Hydrodynamic Model

A regional hydrodynamic model was used to simulate shelf-scale hydrodynamic processes and derive boundary conditions for local scale modelling of the Port Hedland coastal region and SBM site.

Baird's regional hydrodynamic model was established using the Delft3D Flexible Mesh Suite (Delft3D FM). A summary of the key features are as follows (from Deltares, 2018):

- Delft3D FM Suite is a multi-dimensional (1D, 2D and 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on structured and unstructured boundary fitted grids;
- The Delft3D FM Suite can simulate storm surges, cyclones, tsunamis, detailed flows and water levels, waves, sediment transport and morphology, water quality and ecology, and is capable of handling the interactions between these processes;
- D-Flow FM implements a finite volume solver on a staggered unstructured grid. The higher-order advection treatment and near-momentum conservation make the solver very suitable for supercritical flows, bores and dam breaks. The handling of wetting-and-drying makes it suitable for flooding computations; and
- The continuity equation is solved implicitly for all points in a single combined system. Coriolis forcing, horizontal eddy viscosity, tide generating forces and meteorological forcing are incorporated, making the system suitable for tidal, estuarine or river computations.

3.4.1 Model Setup

The Delft3D-FM numerical model grid extent is shown in Figure 3.7. A summary of the Delft3D-FM hydrodynamic model grid and bathymetry setup is as follows:

- The model domain extends across approximately 2000 km of coast and offshore up to 800km.
- A flexible mesh triangular grid with increasing resolution from the offshore to the nearshore areas maximises computational efficiency. Approximate size in offshore areas is 20 km reducing to 500m to 1000m nearshore.
- Bathymetry in the model has been assigned from measured bathymetry and navigational chart information, at a common datum across the model of mean sea level (MSL).

- The model has three offshore boundaries driven by 14 key tidal constituents derived from TOPEX8 (http://volkov.oce.orst.edu/tides/tpxo8_atlas.html, http://volkov.oce.orst.edu/tides/region.html) . The tidal constituents are A0, M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, MN4, MM and MF.
- Bed friction is applied in the model as Manning's roughness values

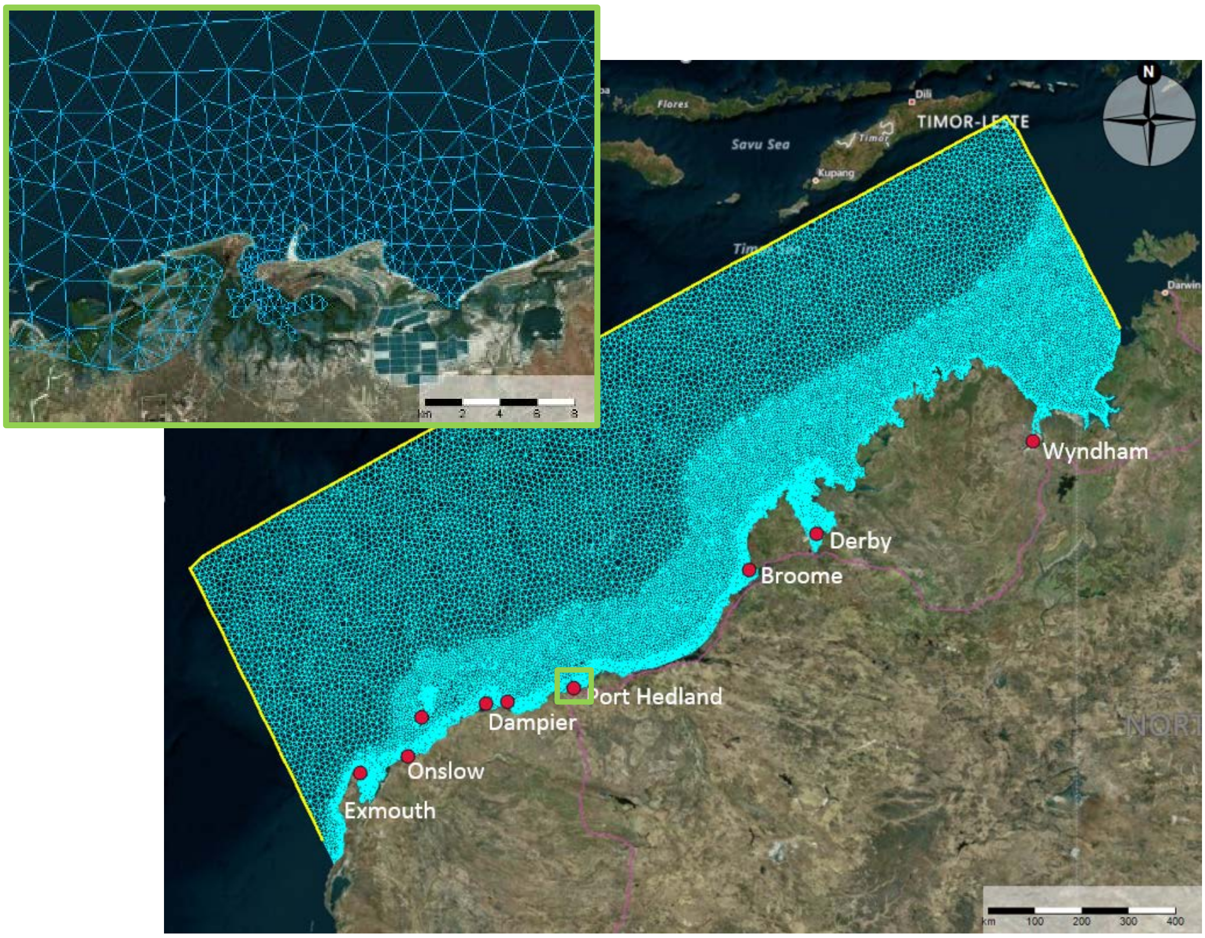


Figure 3.7: Delft3D Flexible Mesh (D-FM) Model Domain of the North West Shelf with detail of model mesh around Port Hedland (insert)

3.4.2 Model Validation

The regional hydrodynamic model has been validated for general tides at Port Hedland and many other key port locations across the north west shelf. A comparison of predicted and modelled tides is shown in Figure 3.8 indicating excellent agreement across the northwest shelf.

The comparison of modelled water level amplitude and phasing against the reported National Tide Centre (NTC) components for the seven primary tidal constituents is shown on Table 3.1 for Port Hedland based on 1 year of tides (2011). The modelled amplitude and phasing results presented in Table 3.1 show very good agreement to the NTC constituents at the port, providing confidence that the model can accurately simulate the astronomical tide across the Port Hedland region.

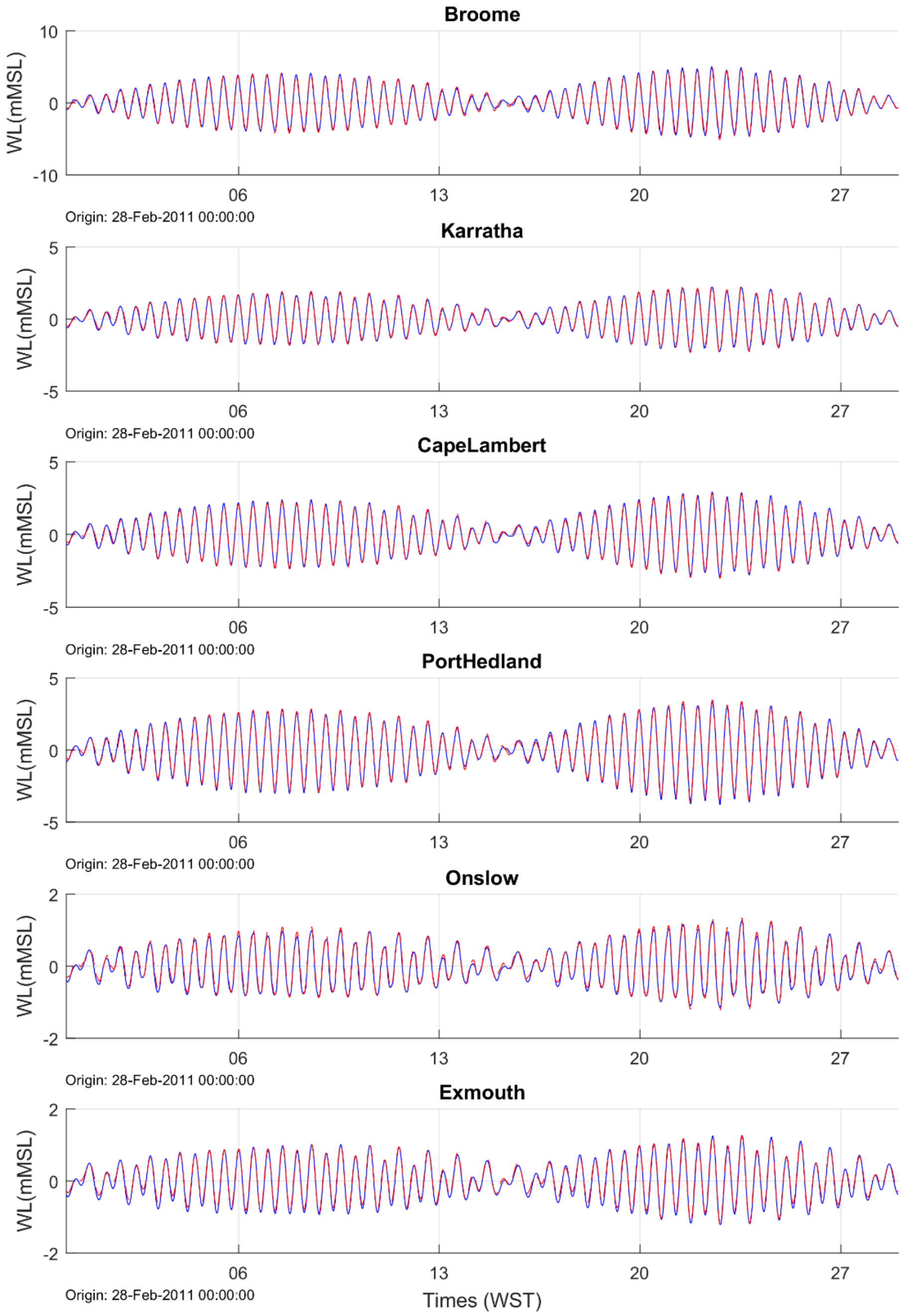


Figure 3.8: Delft3D-FM Hydrodynamic Model Validation: Water Level Comparisons at Six Port Locations on the North West Shelf. Predicted (blue) Modelled (red)

Table 3.1: Model Tidal Validation against NTC Components at Port Hedland

Tidal Constituent	NTC Amplitude	Model Amplitude Difference	Model Phase Difference
M2	1.70	0.7%	-1.3%
S2	1.03	-0.8%	-0.7%
N2	0.29	1.3%	-2.1%
K2	0.29	-1.1%	-0.7%
K1	0.24	0.5%	-0.6%
O1	0.15	4.7%	-0.6%
P1	0.07	8.9%	-0.6%
Q1	0.03	9.3%	-0.6%

The regional hydrodynamic model has also been extensively validated for storm surge, as presented in Taylor et.al. (2018) and Churchill et. al. (2017). For reference, validation of total water level during TC Veronica at Port Hedland Berth 2 is presented in Figure 3.9 with the model replicating the measured data very well.

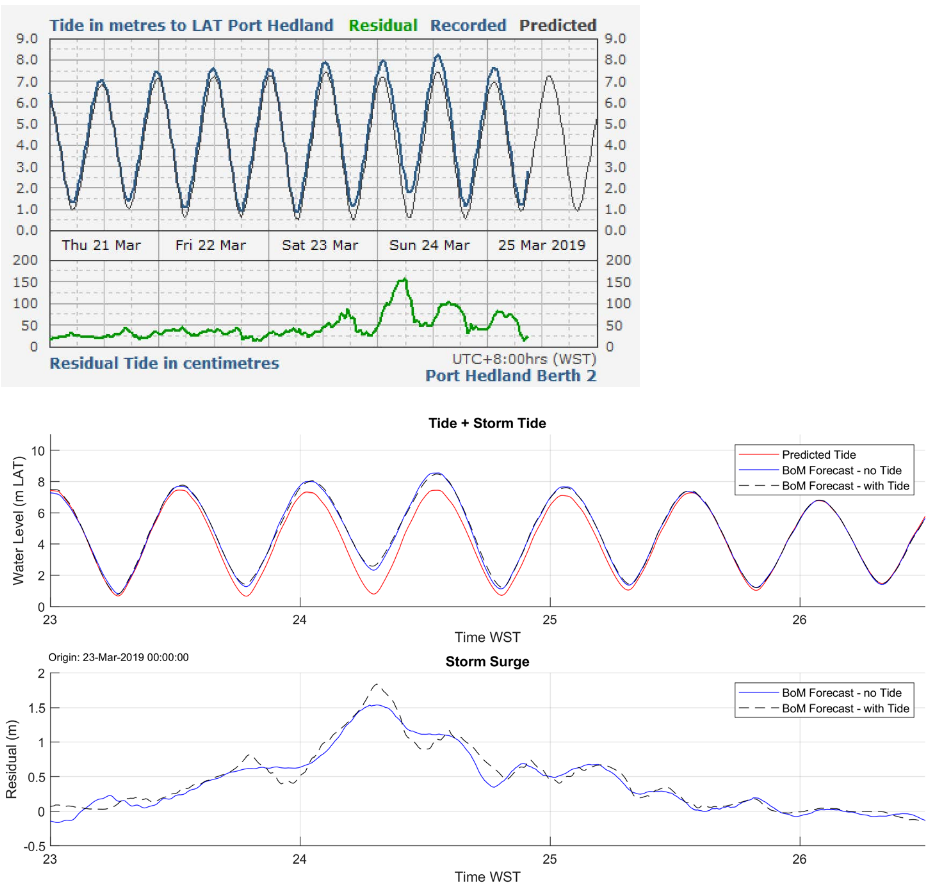


Figure 3.9: Delft3D-FM Hydrodynamic Model Validation: Measured Storm Surge (top) and Modelled Storm Surge (bottom) at Port Hedland Berth 2 during TC Veronica using the BoM Operational Forecast Cyclone Track.

3.5 Regional Wave Model

Regional modelling of cyclone generated wave conditions offshore of Port Hedland was required to develop offshore boundary conditions of spectral waves for local scale modelling. The WaveWatchIII (WW3) model, version 5.16, was adopted for this purpose. WW3 is a third-generation spectral wave model that solves the random phase spectral action density balance equation for wavenumber-direction spectra. The model setup was previously refined and validated for both swell and cyclone dominated conditions on the North West Shelf over a number of studies for other clients of Baird and demonstrated good validation against measured offshore data for over 15 historical events. The regional model extent is presented in Figure 3.10, noting that for ambient/swell conditions the model domain is nested within global and continental scale domains.

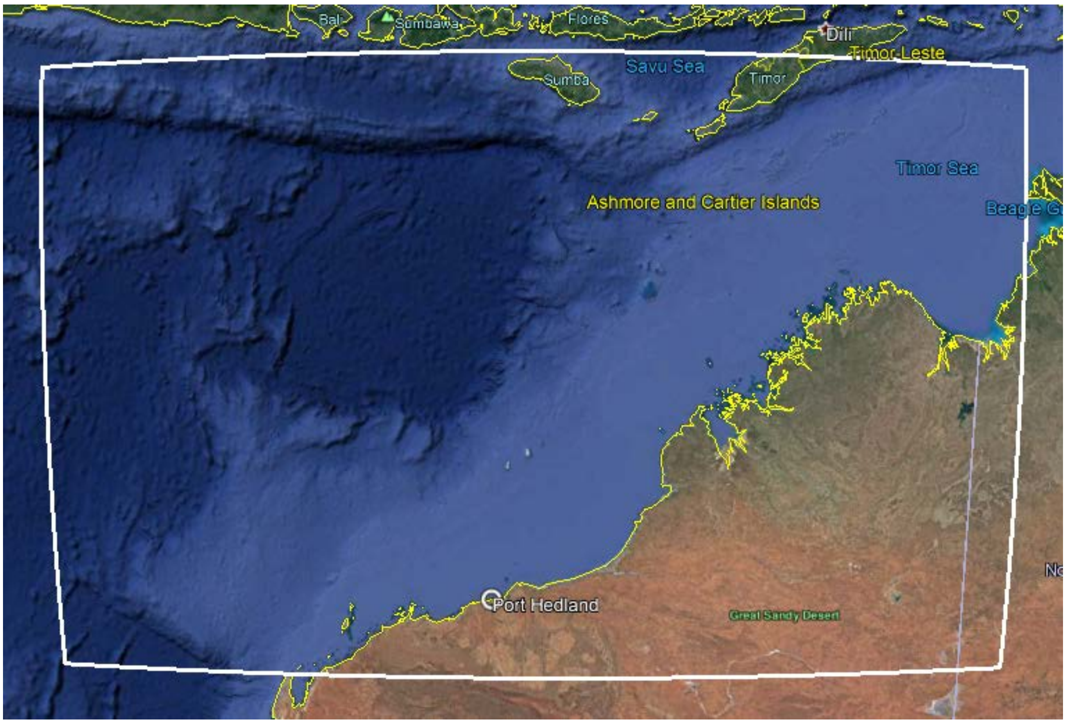


Figure 3.10: Regional WaveWatchIII Model Extent

The setup applied in this study was as follows:

- Spatial grid resolution of 0.07 degrees;
- Spectral direction resolution of 10 degrees (36 direction bins);
- Spectral frequency resolution with frequency scaling factor of 1.1 between frequencies of 0.4056Hz to 0.0412Hz (25 frequency bins);
- ST4 physics scheme;
- JONSWAP bed friction coefficient (Gamma) of -0.038 m^2/s^3;
- Wind forcing developed using Baird's in-house *Cycwind* model, as described above.
- No water level or current forcing.

Figure 3.11 presents the model validation against measured offshore at Beacon C2 (PPA measurement location, see Figure 2.2) for TC Veronica (March 2019). The comparisons indicate excellent agreement between modelled and measured cyclonic wave conditions, with model skills for wave height at 0.99, and provide comparable validation to previous studies of cyclonic wave conditions completed by Baird on the NWS. Comparisons of peak wave period are impacted by the quality of the measured data record, however a peak period of between 12-14 seconds is considered a good representation of the event. The validation indicates that output from the WW3 model can be reliably used as offshore boundary conditions for the local scale model.

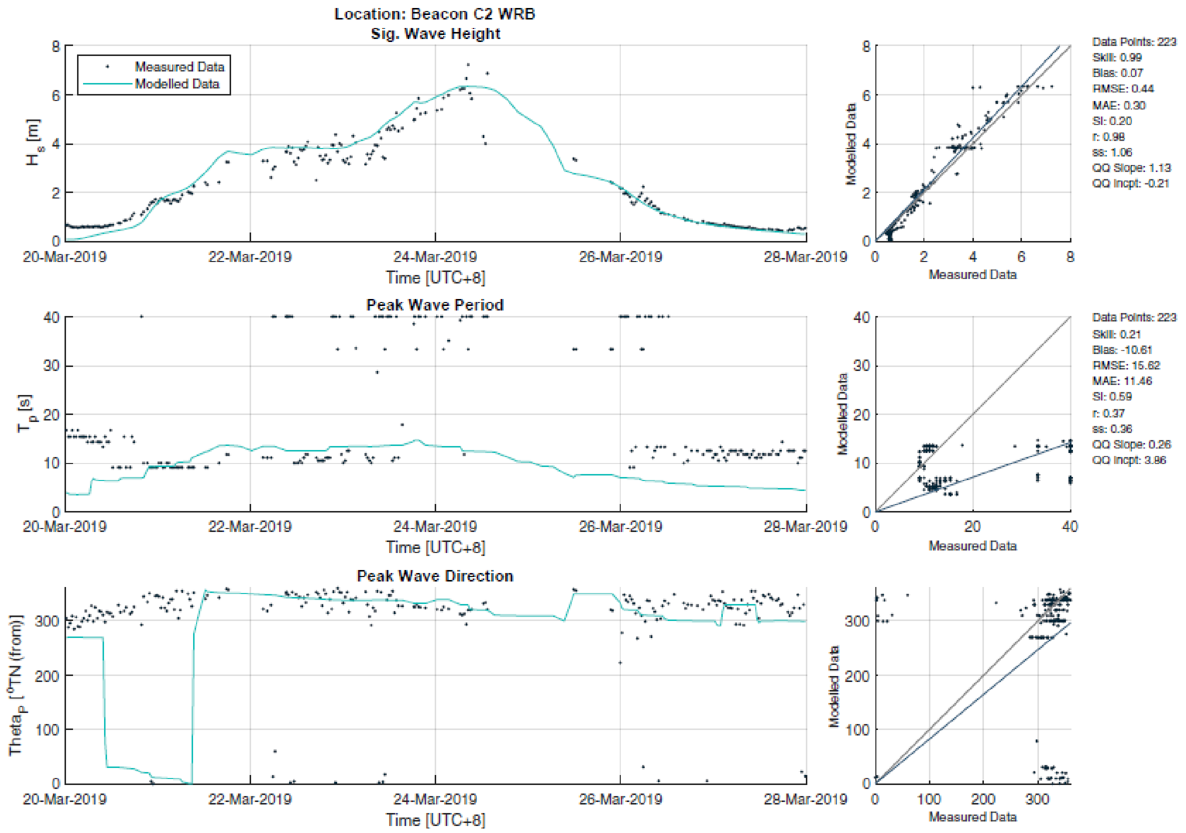


Figure 3.11: WW3 Validation for Tropical Cyclone Veronica at Beacon C2, Offshore Port Hedland

3.6 Local Scale Hydrodynamic and Wave Model

To accurately model the joint occurrence and interaction of water levels and waves, a coupled hydrodynamic and wave modelling approach was applied for local scale modelling over the Port Hedland coastal region and SBM site. The local scale models were forced with offshore boundary conditions derived from the shelf scale hydrodynamic and wave models presented in Sections 3.4 and 0. The Delft3D model system was employed which has previously been adopted by Baird in numerous similar studies and demonstrated to accurately model the storm water level processes at Port Hedland and other coastal locations on the NWS.

Delft3D Flow Wave Flow (FWF)

The local scale Delft3D model allows for coupling of the wave conditions and hydrodynamics through the duration of a cyclone simulation. The modelling approach is termed 'Flow-Wave-Flow' (FWF) with the water levels in the model evaluated in the hydrodynamic model (Flow) and the wave conditions separately evaluated in the waves module (Wave). The key processes affecting water level including radiation stresses are passed across and updated in the hydrodynamic model during the simulation. The FWF process runs continuously through simulation to update and interchange wave and water level information. The effect of waves on current (via forcing, enhanced turbulence and enhanced bed shear stress) and the effect of flow on waves (via set-up, current refraction and enhanced bottom friction) are accounted for within this coupled modelling approach (Deltares, 2015).

Spatial wind and pressure fields active over the model domains influence the wind growth of waves and wind/pressure setup of the water level in the hydrodynamics. Baird's approach is to update spatial wind and pressure fields every 30 minutes for cyclonic conditions and 120 minutes for ambient conditions, and to align coupling interval of hydrodynamics and waves with the input forcing.

Delft3D-Flow Model Setup

The layout of the Delft3D-Flow model is shown in Figure 3.12 and summarised as follows:

- The hydrodynamic model setup is established as a Domain Decomposition model, which allows dynamic two way coupling of structured domains, to maximise the efficiency of the model simulations, with three hydrodynamic grids that increase in resolution from offshore into the SBM site at the entrance to Port Hedland and a fourth covering the Inner Harbour:
  - Outer 315m Grid - extending 40km offshore and approx. 35km east and west of the site;
  - Nearshore 45m Grid – extending to the 10m (approx.) offshore depth contour. Total Grid area 10km x 5km;
  - Local 5m Grid - overlays the Spoilbank and adjacent nearshore and channel areas. Total Grid Area 3.5km x 4km.
  - Inner Harbour 45m Grid – covering the Port Hedland Inner Harbour and intertidal tributaries.
- Boundary conditions at the outer boundary are derived from hydrodynamic output from the regional scale hydrodynamic model (see Section 3.4). These are input as time series of water levels across boundary points at approximately 5km interval around the outer domain;
- A model timestep of 0.25 minutes (15 seconds) was adopted.

Previous validation of a local scale Delft3D coupled hydrodynamic/wave model for Mermaid Sound (Karratha) determined that a change in the model wind drag coefficients produced improved validation for storm surge and tide for historical cyclone cases. Full details are documented in Churchill et al (2017). The same wind drag parameterisation was therefore applied to both the Delft3D Flow and regional scale Delft-FM models for this study. The adopted wind drag coefficient, as a function of wind speed, was:

- Wind Speed (m/s) = 0 20 60
- Wind Drag Coefficient (Cd) = 0.001 0.0025 0.0025

Note the above wind drag coefficients are applied to the hydrodynamic (Flow) model, the adopted Wave model applies an uncapped drag coefficient that is considered conservative for development of cyclonic design criteria as described below.

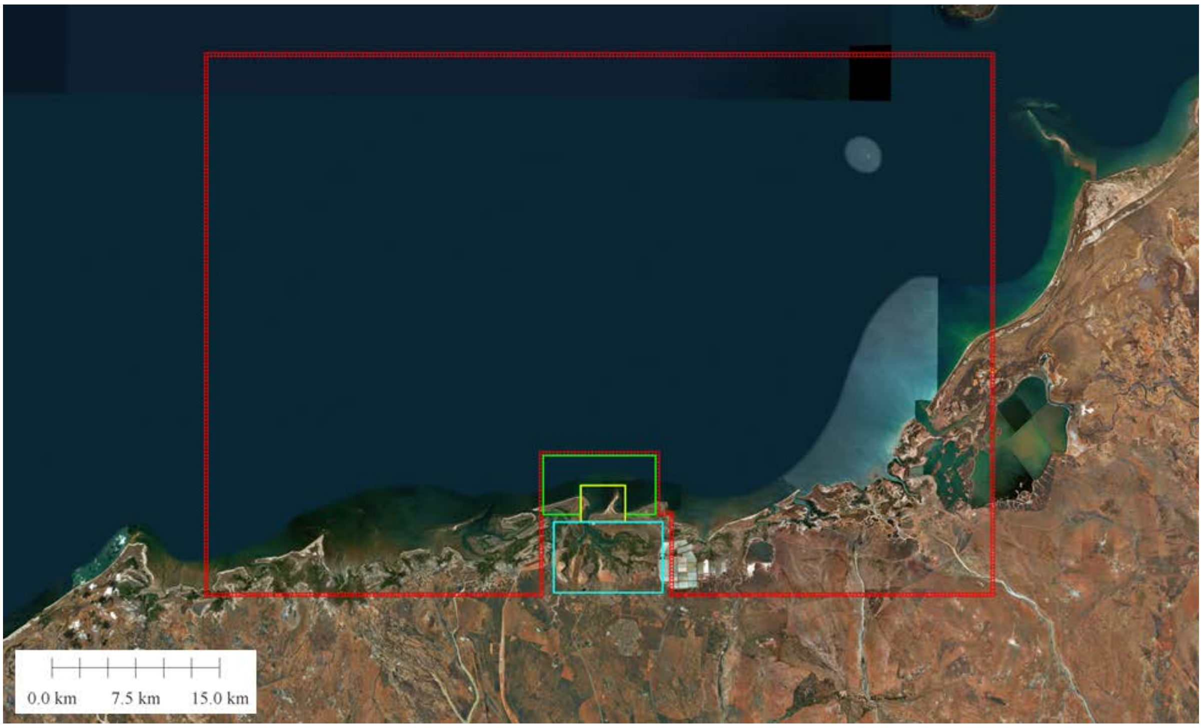


Figure 3.12: Local Delft3D Flow-Wave-Flow Model Layout. Outer grid (red) is 315m resolution, Nearshore grid (green) is 45m resolution, Local grid (yellow) is 5m resolution and the Inner Harbour grid (blue) is 45m resolution.

Delft3D-Wave Model Setup

The Delft3D-Wave system applies the Deltares SWAN (Simulating WAves Nearshore) model which is a 3rd generation spectral model. The SWAN model was used to both transfer wave conditions from offshore and develop locally generated wave conditions and propagate the resulting wave energy to the Mermaid Sound facilities under extreme cyclonic wind forcing.

The SWAN model can account for the following physics (Deltares, 2015):

- wave refraction over a bottom of variable depth and/or a spatially varying ambient current;
- depth and current-induced shoaling;
- wave generation by wind;
- dissipation by whitecapping;
- dissipation by depth-induced breaking;
- dissipation due to bottom friction (three different formulations);
- nonlinear wave-wave interactions (both quadruplets and triads);
- wave blocking by flow;
- transmission through, blockage by or reflection against obstacles; and
- diffraction.

The model grid layout and resolution replicate the Delft3D flow model, increasing in resolution from offshore to the Spoilbank area (see Figure 3.12), however the Inner Harbour grid is excluded.

- The bed friction in the model is based on a JONSWAP bottom friction formulation value of 0.067 m^2/s^3 which was found to be suitable for cyclonic wind sea conditions (consistent with Deltares 2018). The bottom friction value used in the SWAN model is larger than the value applied in the WW3 model, noting that the regional scale WW3 model is not overly sensitive to the JONSWAP bottom friction value where a lower value of 0.038 m^2/s^3 was found to be most appropriate for the physics scheme applied and offshore wave depths being modelled;

- Offshore boundary conditions were applied as directional spectra derived from the shelf scale WW3 model (see Section 0). The boundary points were spaced at approximately 5km interval around the outer domain.

3.6.1 Model Validation – Tidal Hydrodynamics

Validation of the tidal hydrodynamics was completed for a spring neap phase during benign offshore conditions in February 2019. Comparisons of the modelled water level and currents at the DoTHD01 AWAC location (see Figure 2.2) is presented in Figure 3.13. Appendix B includes the same presentations at the DoTHD02 location as well as water levels at three PPA water level gauges.

Water level calibration is good across all sites with very high model skill, and low bias and error statistics.

To provide a like-for-like comparison of current speeds, the depth averaged values from the model were adjusted to reflect the 0.6m blanking distance between the seabed and the lowest recorded depth from the AWAC. The resulting comparisons show good agreement for current speed and direction, with a slight offset in the directions observed. This is thought to be a result model schematisation of the seabed at location in close proximity the steep navigation batters.

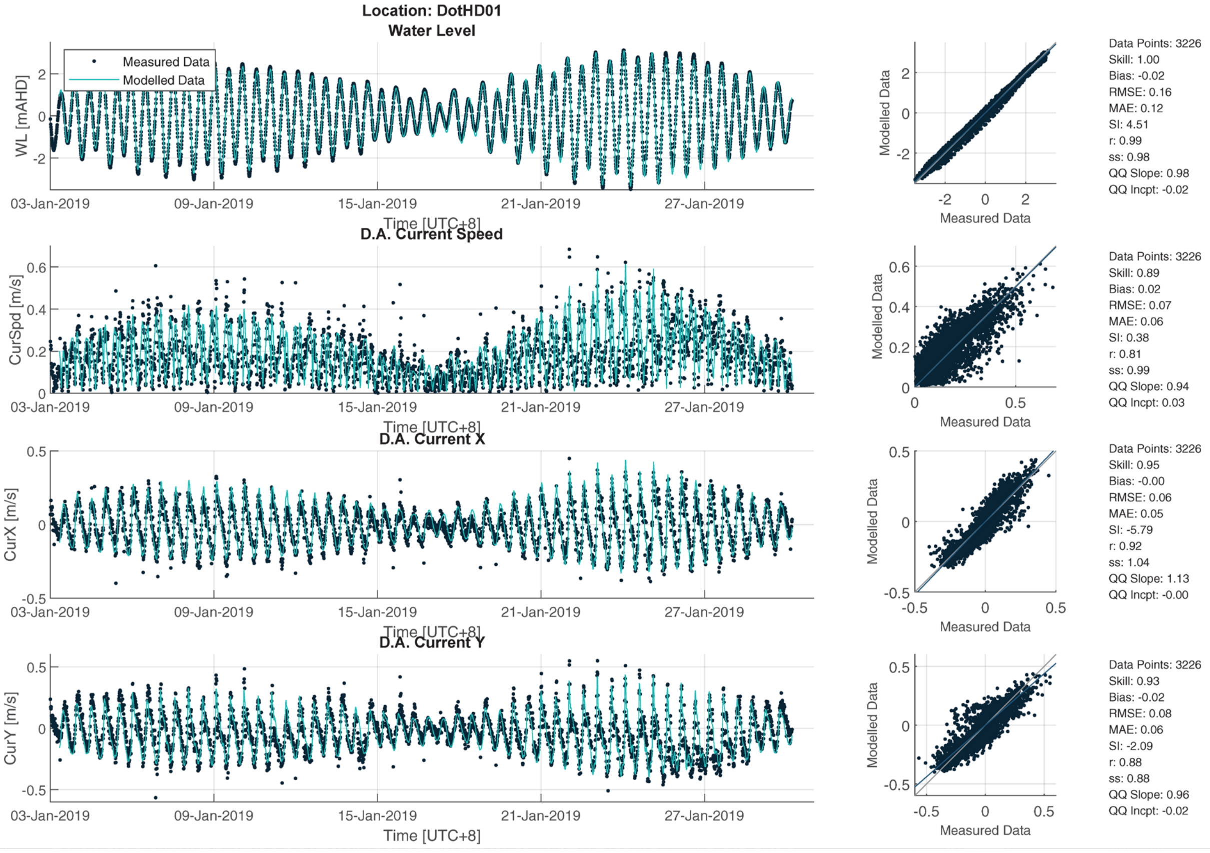


Figure 3.13: Water level and Current Validation at the DoTHD01 AWAC location

3.6.2 Model Validation – Cyclonic Conditions

Validation of the FWF model system for the simulation of storm surge and waves during cyclonic events was undertaken for TC Veronica, that impacted Port Hedland in 2019. The event is an ideal candidate storm for model validation as the DoT's measurements campaign captured water level, current and wave data during the event at two locations in close proximity to the proposed SBM (see Section 'Available Metocean Data' above and Baird, 2019).

Cyclonic wind and pressure fields for the event were modelled with Baird's in-house *Cycwind* program as presented in the Sections above.

The modelled timeseries of water levels and waves are compared against the measured data at the DoTHD02 AWAC location (see Figure 2.2) in Figure 3.14 and Figure 3.15. Appendix B includes the same presentations at the DoTHD01 location as well as water levels at three PPA measurement locations.

Near the Spoilbank (DotHD01 & DoTHD02 AWAC locations), the modelled event replicates the observed hydrodynamic and wave conditions reasonably well. Peak water levels are ~0,2m higher, however match observation at Beacon 47 very well. Wave heights are being over-estimated by ~20%, however this is an appropriate outcome for the development of metocean design criteria at the site given the limitations of the instruments in measuring the surface signal in turbulent breaking wave conditions.

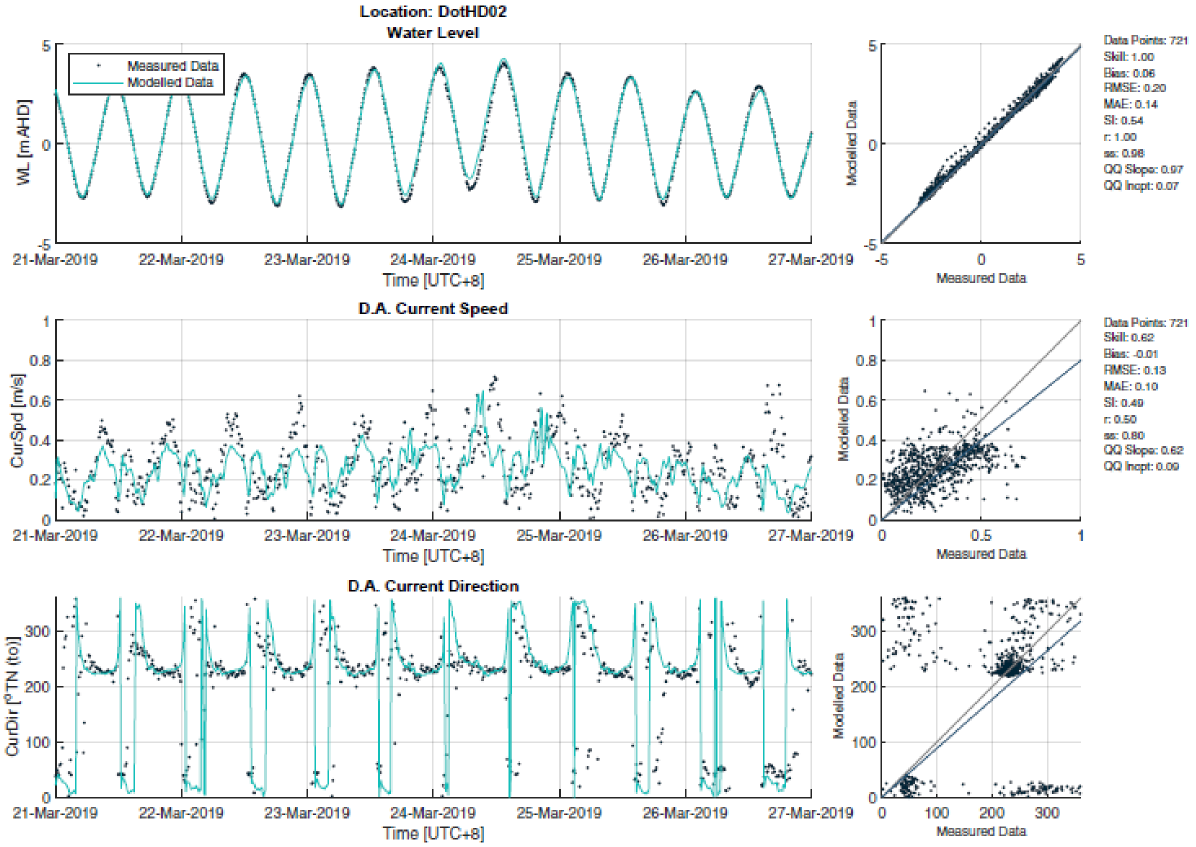


Figure 3.14: Water level and Current Validation at the DoTHD02 AWAC location during TC Veronica (March 2019)

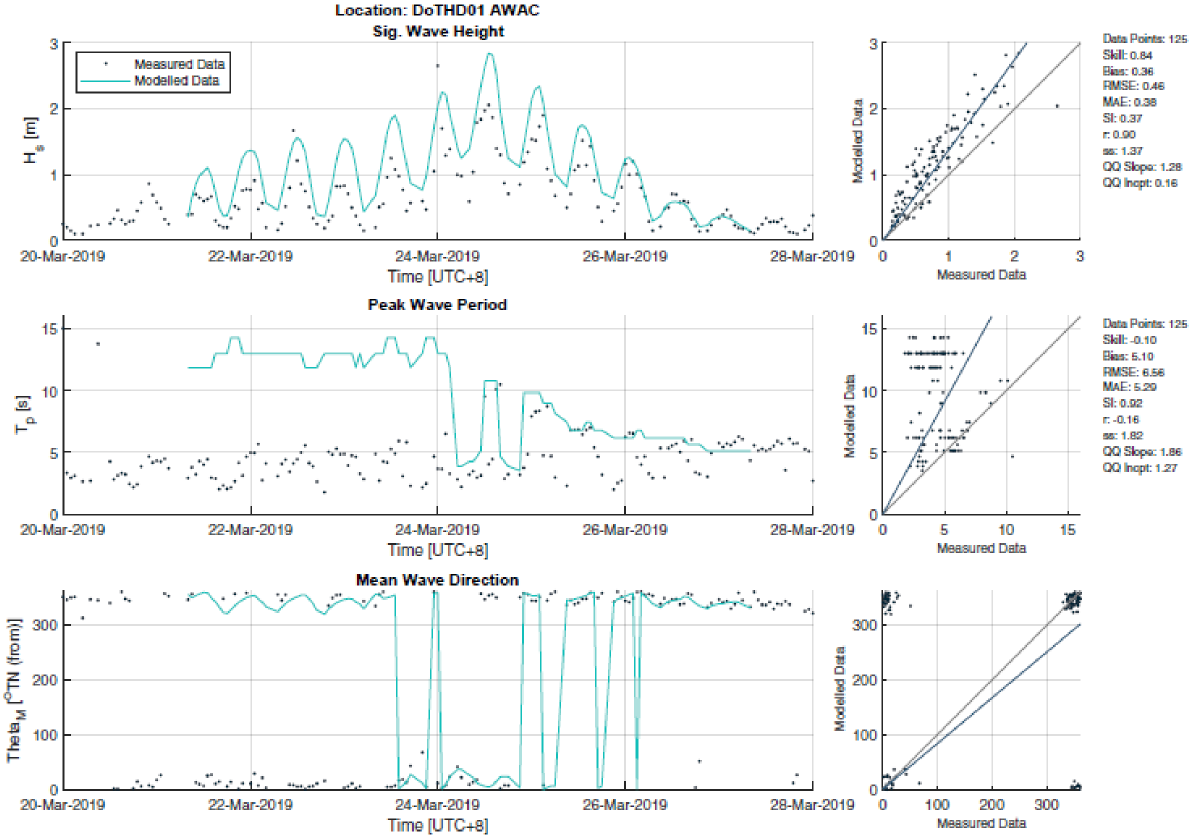


Figure 3.15: Wave Condition Validation at the DoTHD01 AWAC location during TC Veronica (March 2019)

3.7 Hydrodynamic Changes due to the Development

Although the proposed SBM is outside the main navigation channel, and hence not within the main conveyance path in and out of the harbour, the SBM entrance structures will act to block and re-direct current flows around them. Given the large tide range at Port Hedland, hydrodynamics throughout Port Hedland and at the proposed SBM location are dominated by tidal induced flows. However, under cyclonic conditions, storm surges and extreme wind speeds would produce a notable residual in the current speeds, as observed during TC Veronica (see Section 2.4).

Hydrodynamic simulations, using the calibrated Delft3D hydrodynamic model, were undertaken to assess the influence that the proposed SBM would have on both ambient and storm induced currents at the Spoilbank and the broader Port Hedland area.

3.7.1 Ambient Conditions

The Delft3D model was run both with and without the inclusion of wind, for the model calibration period. Comparison of these model runs demonstrated that over the entire one-month simulation, for both the summer and winter cases, ambient wind conditions generally had a minor effect of less than a 0.05 m/s impact on currents along the western shore of the Spoilbank. Furthermore, ambient wind conditions can either have a negative or positive impact on current magnitudes, depending on the relative direction that the wind is blowing compared to the current direction at the time. It can therefore be inferred that currents in the region of the proposed SBM are almost entirely tidally driven, and that the contribution from wind is generally negligible under ambient conditions. The assessment of the proposed SBM on local ambient currents is therefore not seasonally dependent.

The month of January 2019 was simulated to represent tidal conditions across the Spoilbank area. The simulation was run for both existing conditions and with the inclusion of the proposed SBM to assess the impact of the new development on local currents. During this period a large spring tide, with a tidal range of 5.7m, occurred on the 24 January 2019 and was used for pre- and post- SBM development comparisons.

Under existing conditions, both measurements and hydrodynamic modelling identify a relatively consistent flow structure with a tidal flow inequality resulting in stronger flood tide currents and weaker ebb tide flows. Figure 3.16 and Figure 3.17 present the modelled current fields for existing conditions for a peak spring flood and peak spring ebb tide. During ebb tides the outgoing flows from the Inner Harbour are predominantly contained to the main navigation channel and as a result ebb tide current magnitudes over the natural seabeds in the vicinity of the SBM entrance are 0.07m/s (max). Flood tide currents close to the entrance location are 0.23m/s (max) increasing to 0.45m/s (max) over the length of the SBM entrance channel.

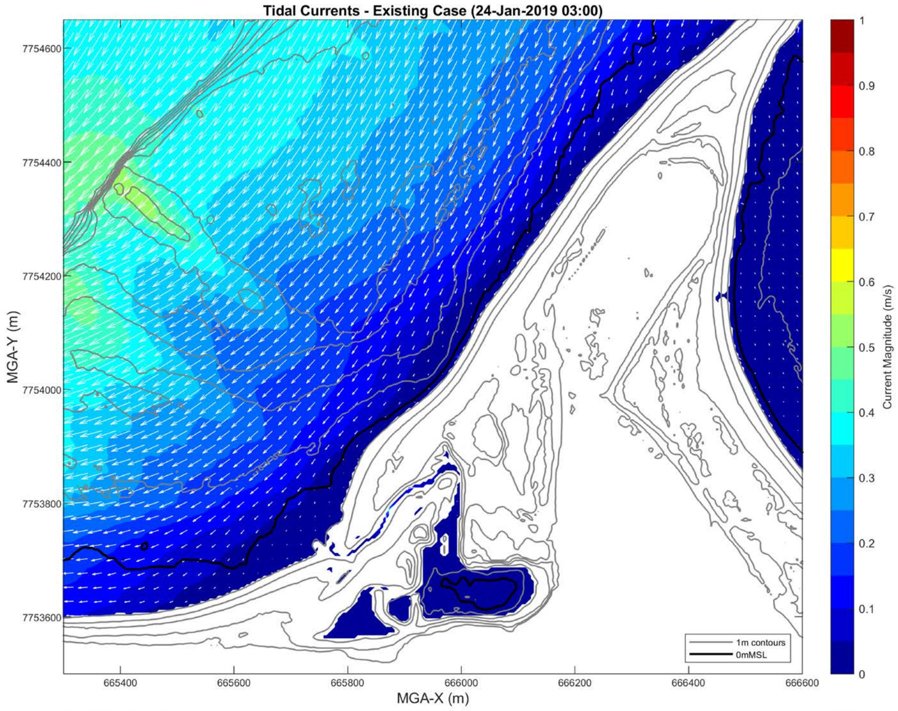


Figure 3.16: Peak Spring Flood Tide Current Map under Existing Conditions in the Vicinity of the Spoilbank Marina

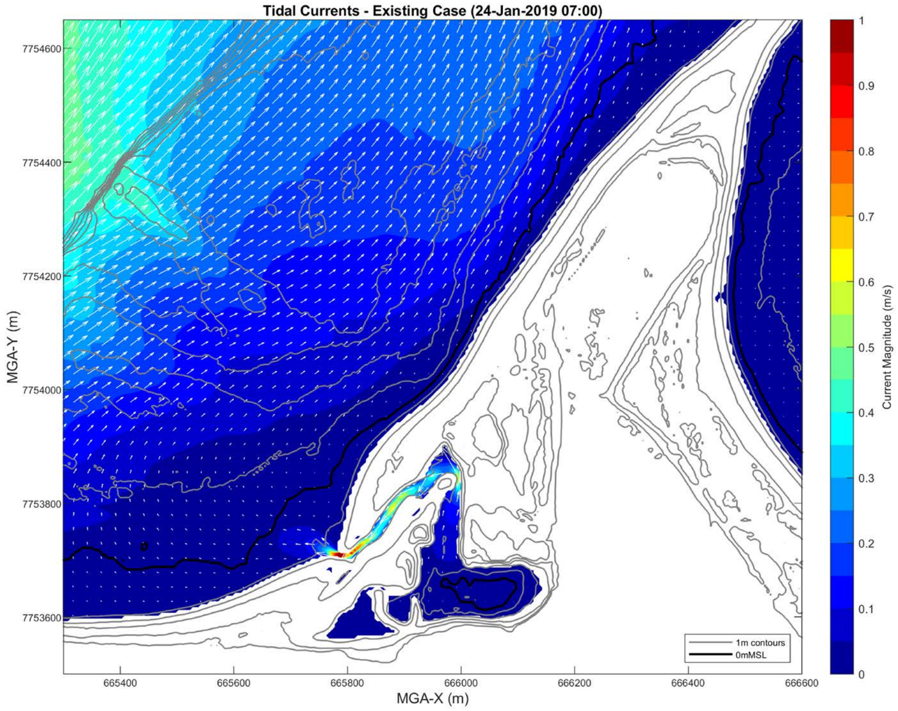
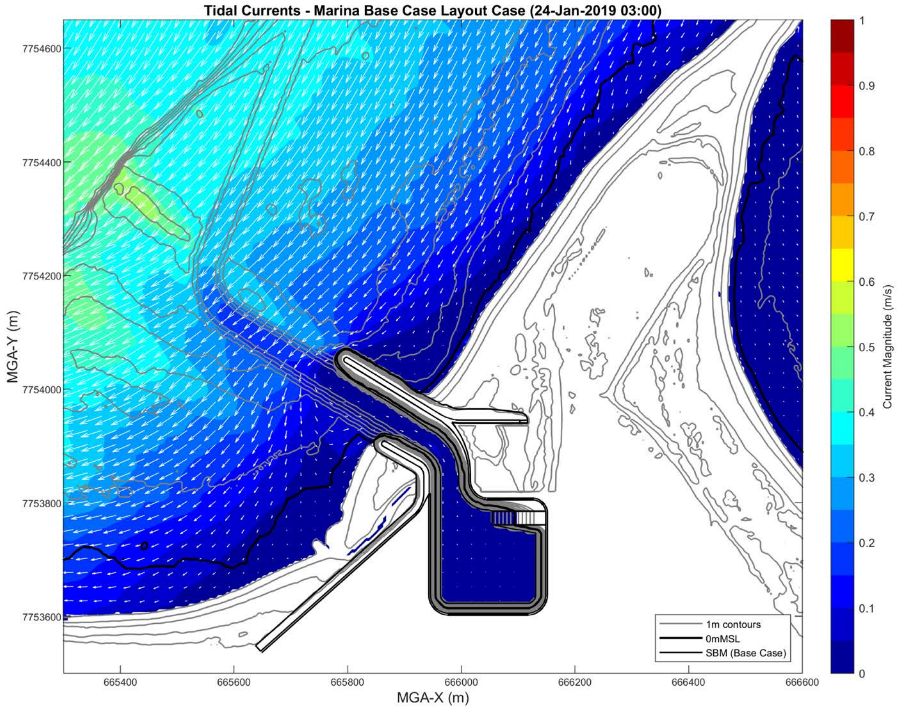


Figure 3.17: Peak Spring Flood Tide Current Map under Existing Conditions in the Vicinity of the Spoilbank Marina

The following set of figures present the modelled current fields for the four marina layout and channel option combinations for a peak spring flood and peak spring ebb tide (same timesteps as existing case presentations above) along with the difference maps that identify the magnitude change in current speed as a result of the development.

- Figure 3.18 and Figure 3.19 present the Base Case layout with Option 1 channel
- Figure 3.20 and Figure 3.21 present the Option 1 layout with Option 1 channel
- Figure 3.22 and Figure 3.23 present the Base Case layout with Option 2 channel
- Figure 3.24 and Figure 3.25 present the Option 1 layout with Option 2 channel
- Figure 3.26 and Figure 3.27 present the Option 2 layout with Option 2 channel

Overall the inclusion of the proposed SBM has only a small and localised impact on the tidal currents through the area. Given that the marina basin is to be constructed in-land (within the Spoilbank landmass) and outside of the existing harbour waters, this result is to be expected. The relatively small basin volume and entrance width results in a relatively small exchange of water between the SBM basin and port waters, with negligible currents observed within the SBM basin itself. Some localised changes to tidal currents are observed near the SBM entrance due to the marina entrance channel and protrusion of the entrance breakwater structures. Most of the changes result in a decrease in tidal currents due to seabed deepening through the entrance channel and sheltering/redirection of flows by the entrance structures, which is less pronounced for Channel Option 2 during flood tides; due to the alignment of the Option 2 channel being more in keeping with the principal tidal stream. However, on flood tides, the constriction of flows around the northern breakwater head locally increases flows by up to 0.1m/s. It would be expected that the seabed would locally respond to this increase in currents, however the increase is not considered material to the stability of the breakwater heads. This will be further investigated as part of the sediment transport assessment.



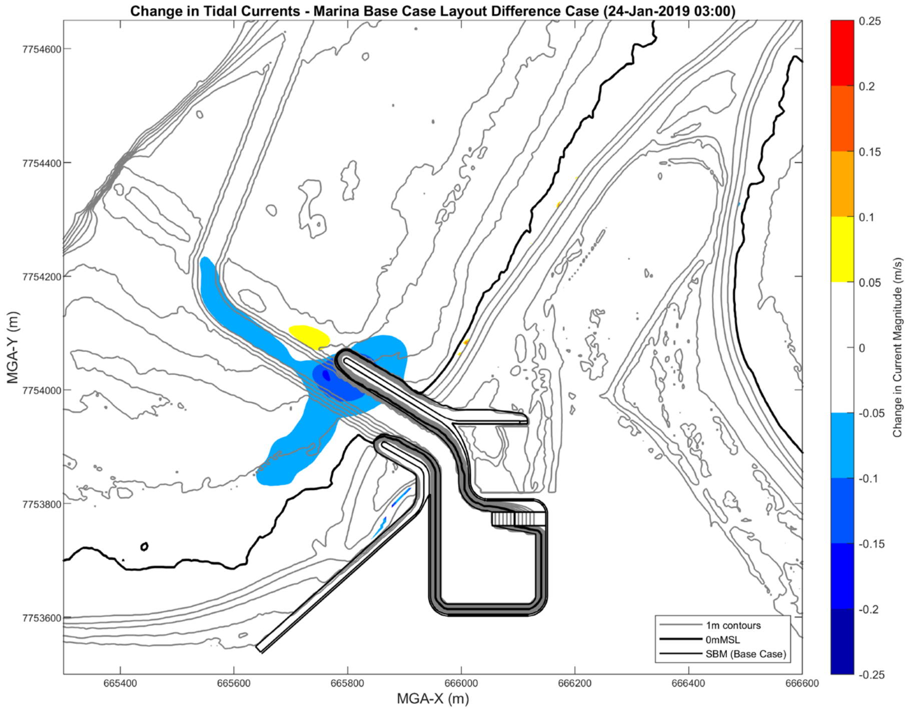
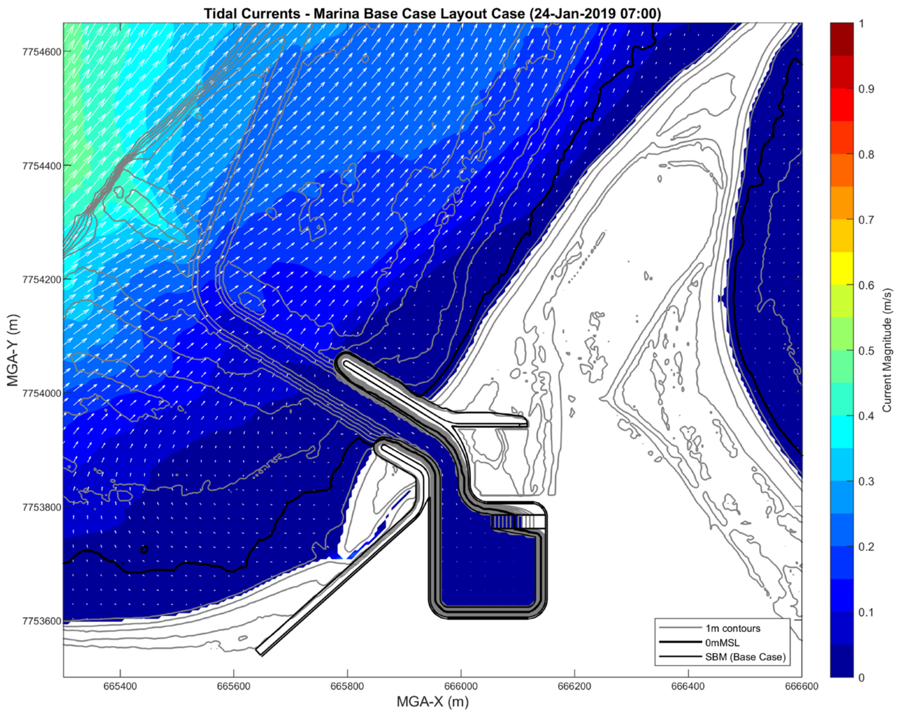


Figure 3.18: Peak Spring Flood Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Base Case Marina Layout with Channel Option 1) in the Vicinity of the Spoilbank Marina



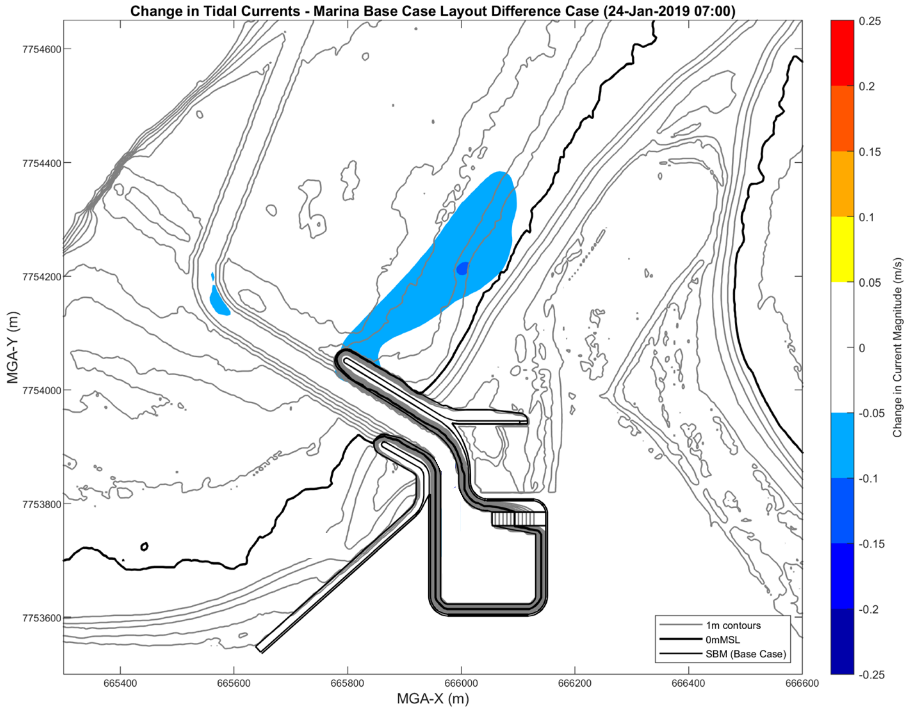
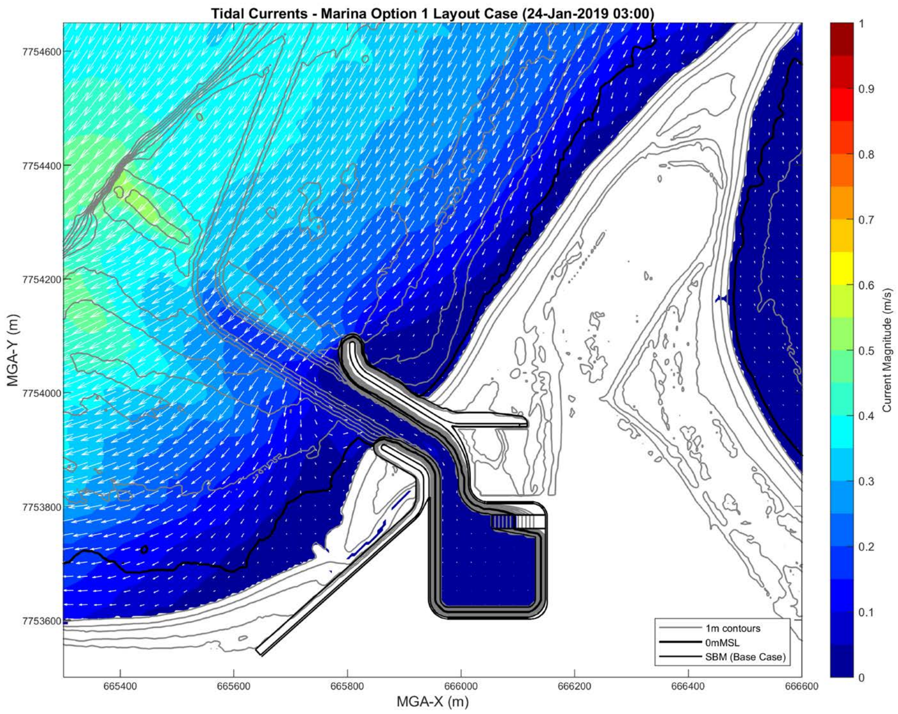


Figure 3.19: Peak Spring Ebb Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Base Case Marina Layout with Channel Option 1) in the Vicinity of the Spoilbank Marina



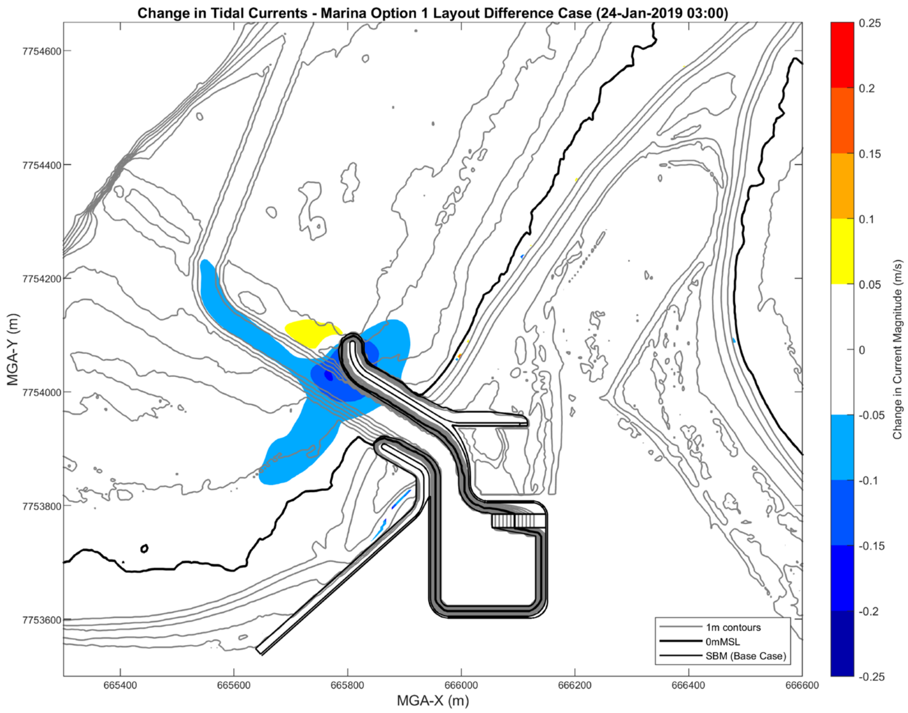
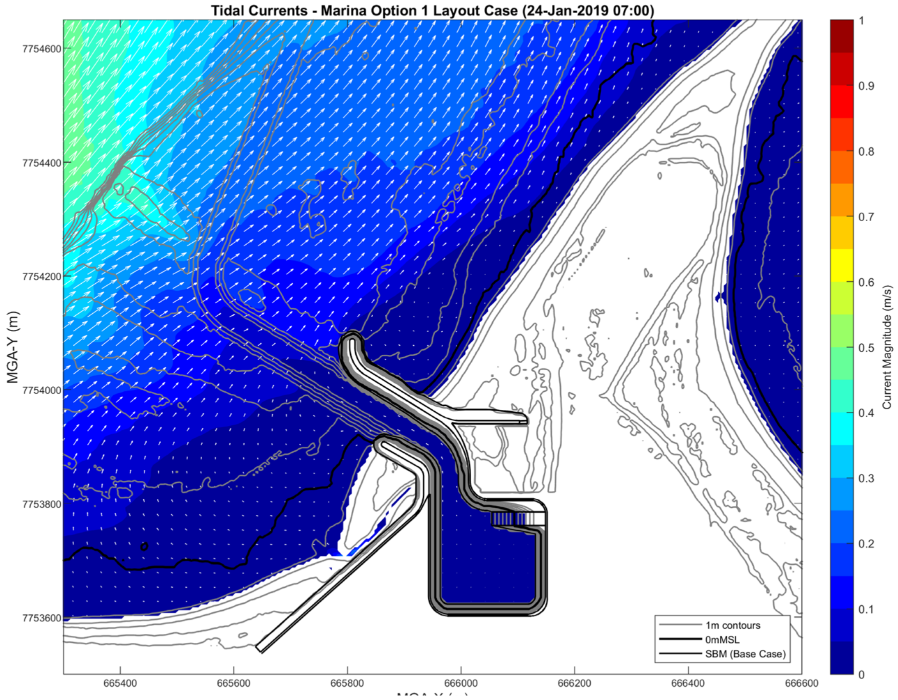


Figure 3.20: Peak Spring Flood Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 1 Marina Layout with Channel Option 1) in the Vicinity of the Spoilbank Marina



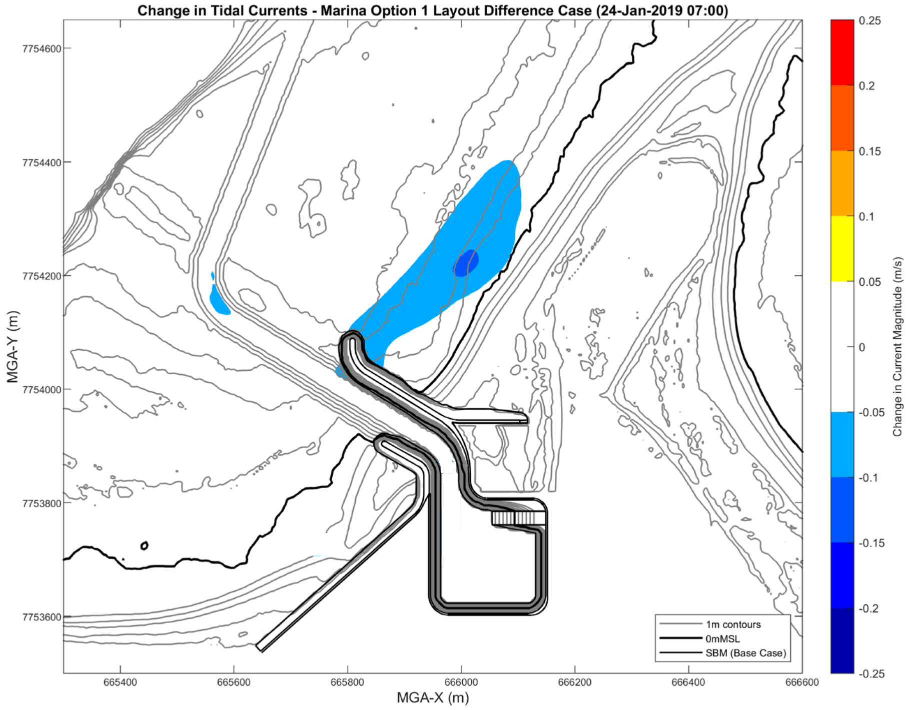
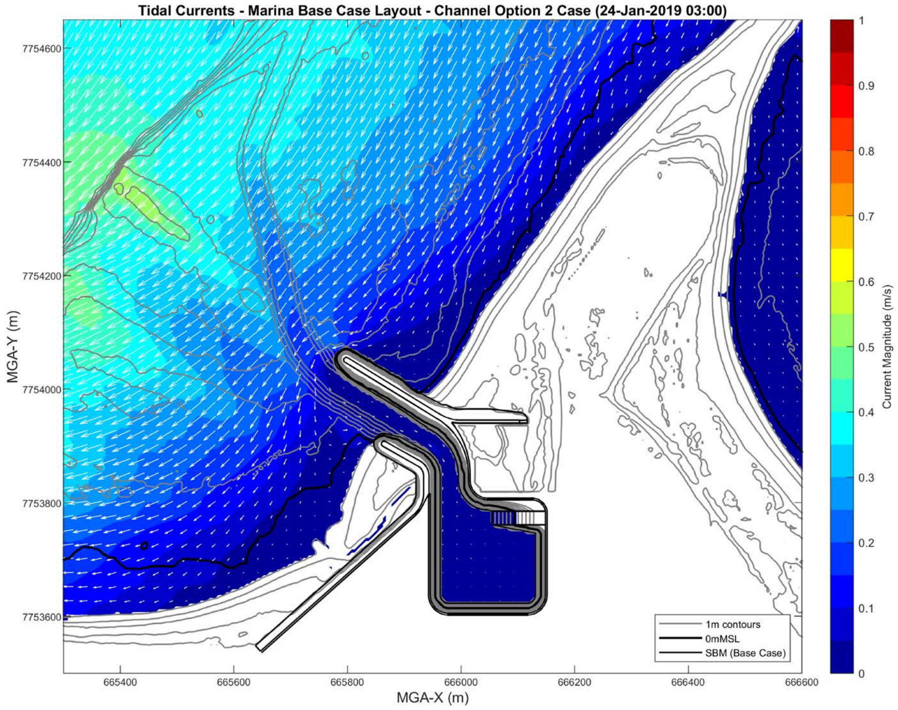


Figure 3.21: Peak Spring Ebb Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 1 Marina Layout with Channel Option 1) in the Vicinity of the Spoilbank Marina



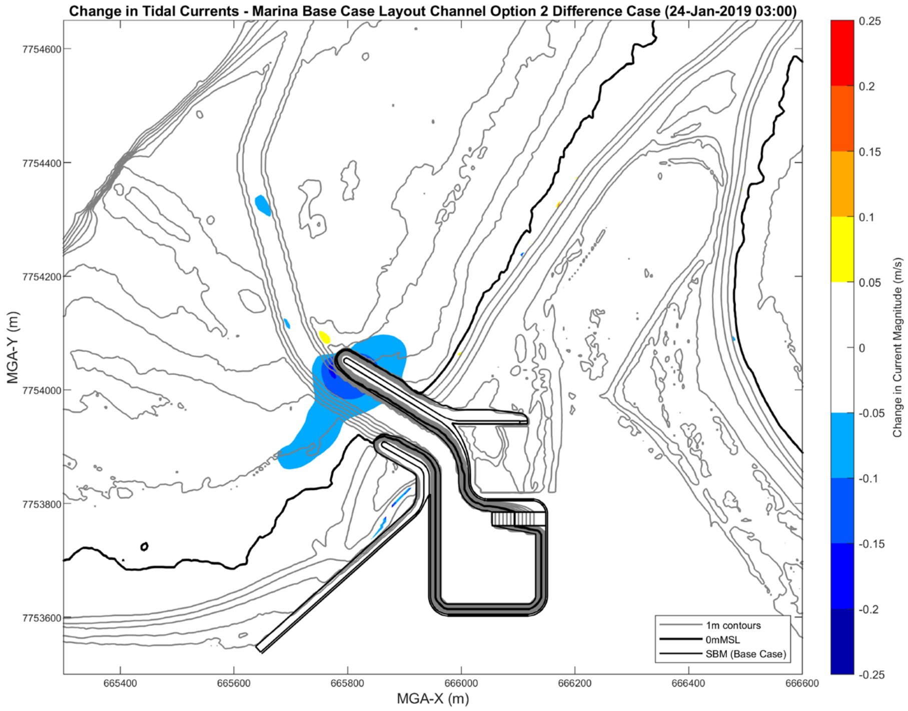
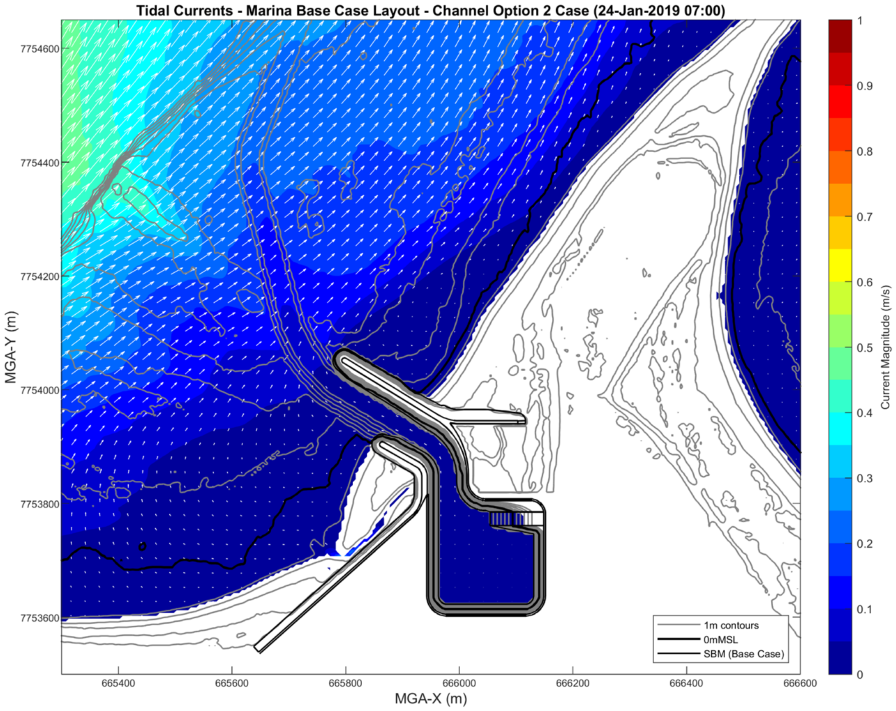


Figure 3.22: Peak Spring Flood Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Base Case Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina



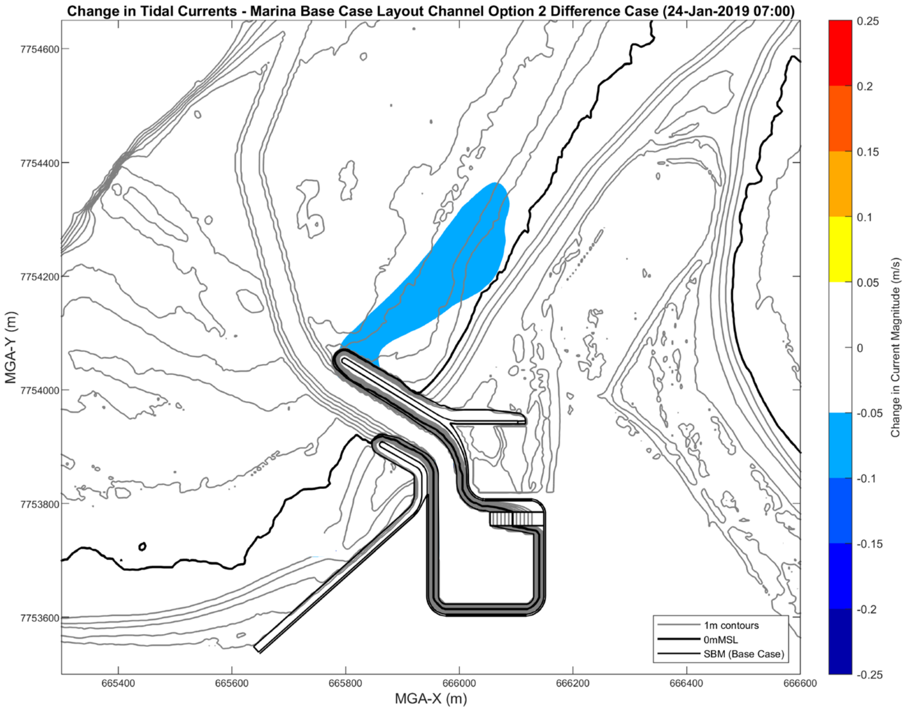
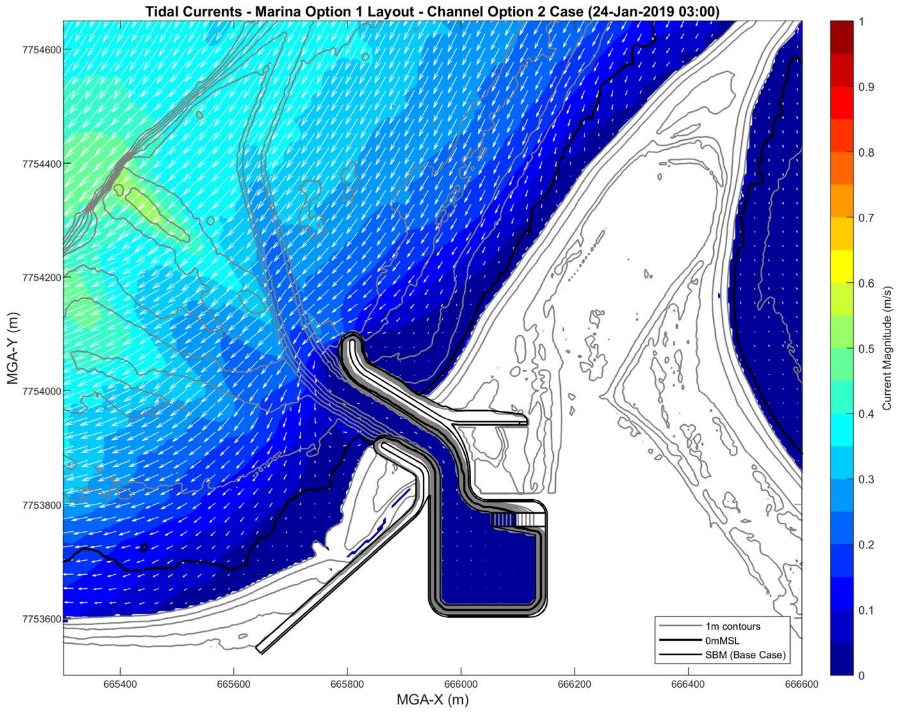


Figure 3.23: Peak Spring Ebb Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Base Case Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina



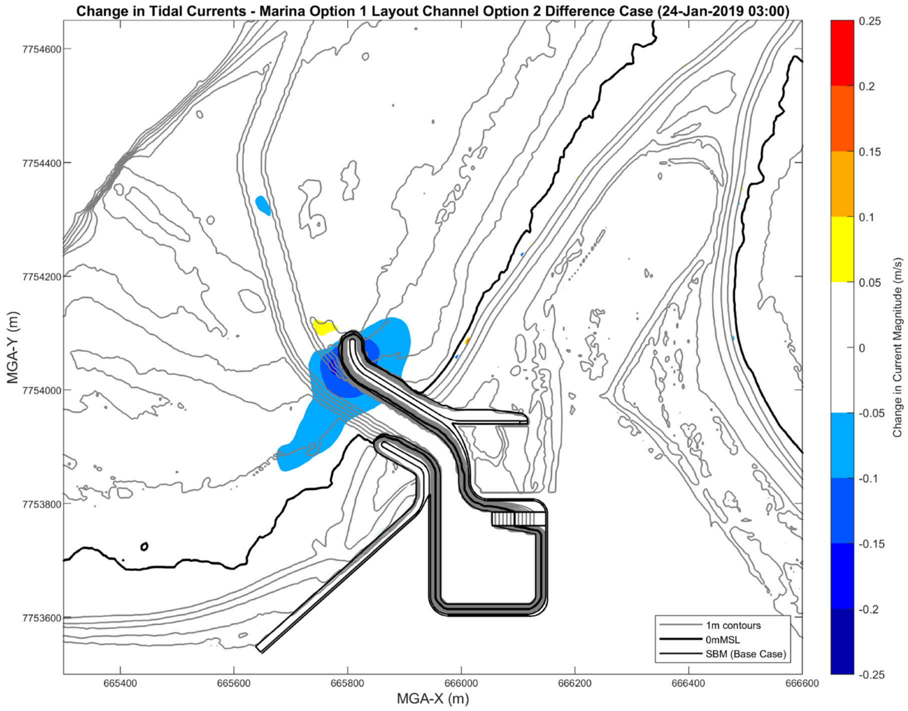
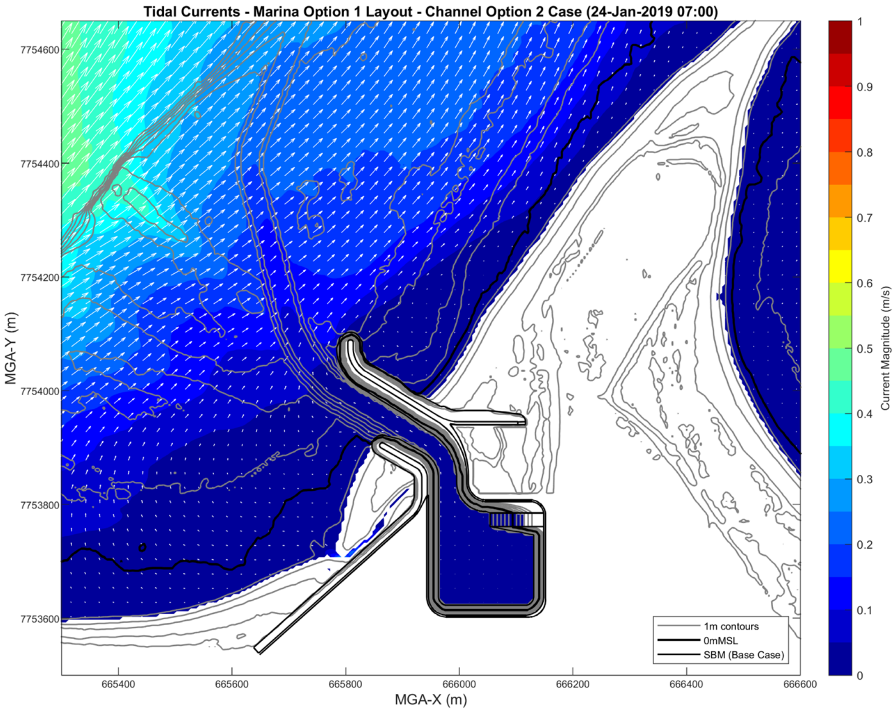


Figure 3.24: Peak Spring Flood Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 1 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina



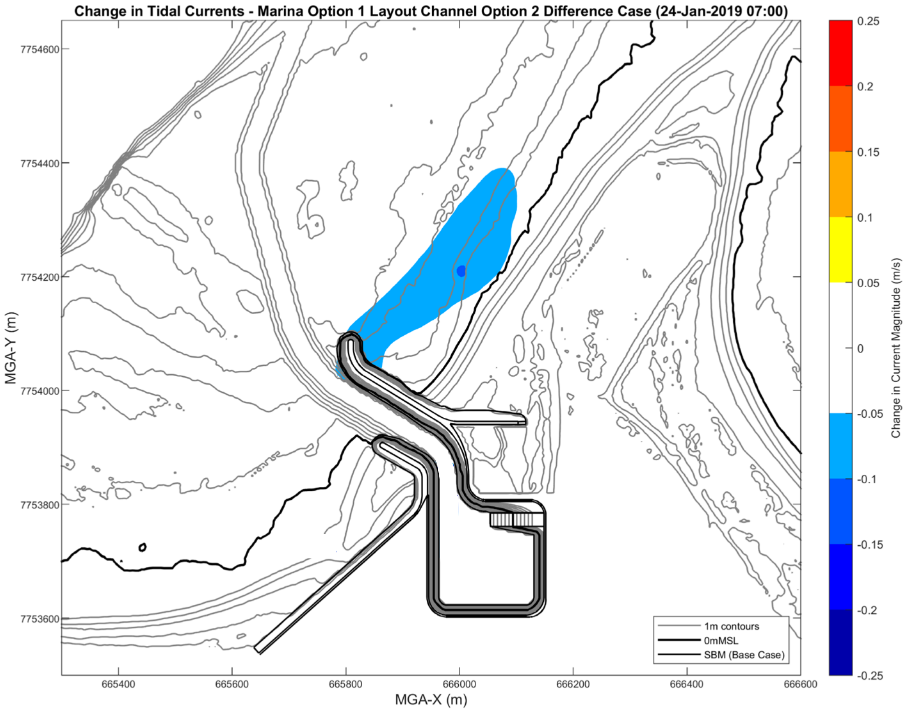
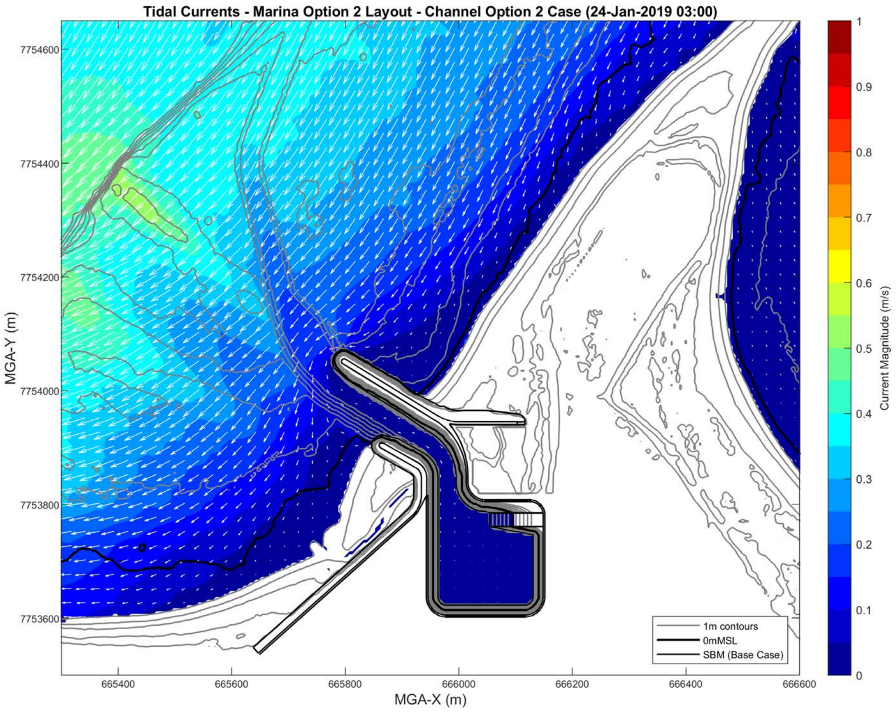


Figure 3.25: Peak Spring Ebb Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 1 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina



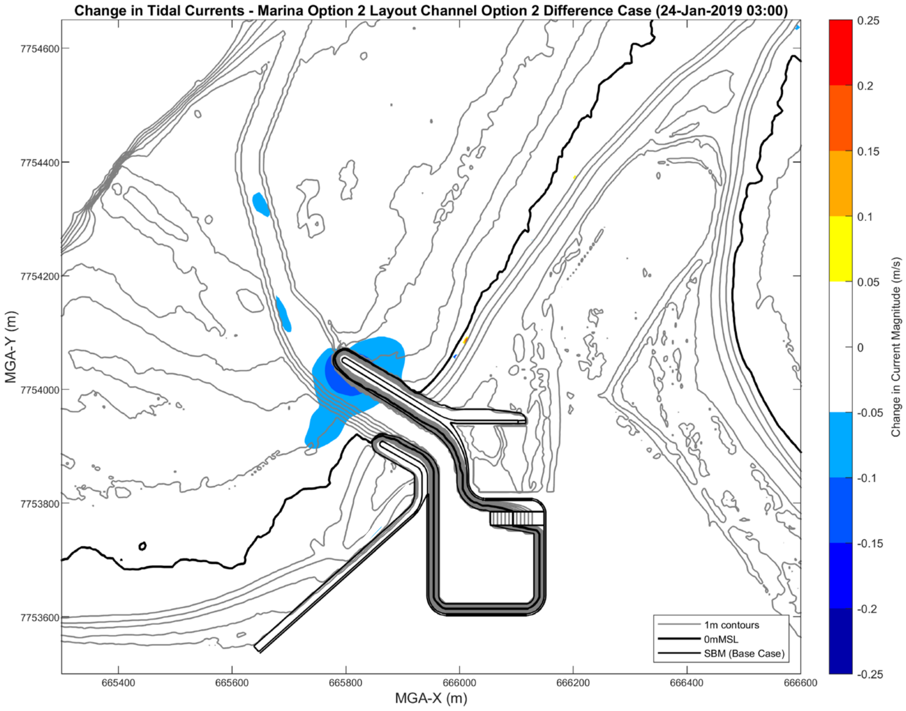


Figure 3.26: Peak Spring Flood Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 2 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina

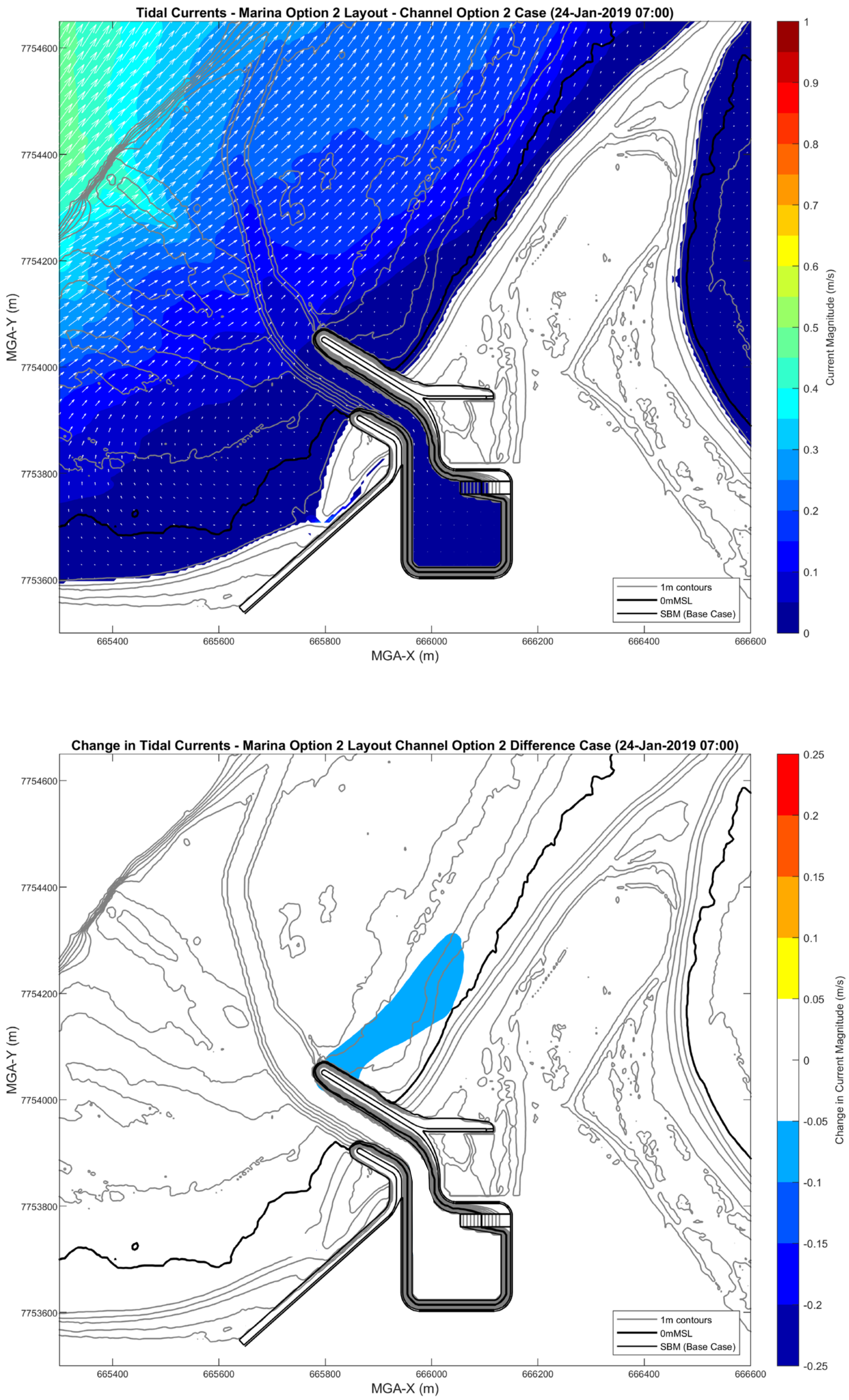


Figure 3.27: Peak Spring Ebb Tide Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 2 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina

3.7.2 Cyclonic Conditions

During cyclone events stronger currents are typically observed due to wind induced currents and the high peak water levels resulting from storm water levels. To investigate the influence of the SBM marina on storm induced hydrodynamics, the design storm representative of the 100-year ARI wave and water level conditions (see Section 4.1 for definition) was simulated using the coupled Deft3D hydrodynamic and wave model, in order to account for wave-current interaction that is expected during the extreme events.

Figure 3.28 shows the peak storm-induced currents across the entrance area of the proposed marina under existing conditions. Wind induced current speeds of up to 0.7m/s (depth-averaged) are generated across the broader nearshore area increasing to ~1.0m/s (depth-averaged) to the south west as the flows approach the shoreline adjacent to the southern end of Spoilbank. Further, a significant along-shore current in depths of between 1 and 4m is established, as a result of the incoming waves, flowing directly across the SBM entrance area. These results can be considered typical of peak current flows resulting from extreme cyclone events.

The modelled current fields under extreme cyclone conditions for the four marina layout and channel option combinations are presented in the section below. As was observed under ambient tidal conditions, changes to hydrodynamic flows during storm everts are localised and do not extend beyond the proposed marina entrance. The presence of the entrance structures diverts the alongshore flows and peak current speed at the head of the northern breakwater increase by up to 35%.

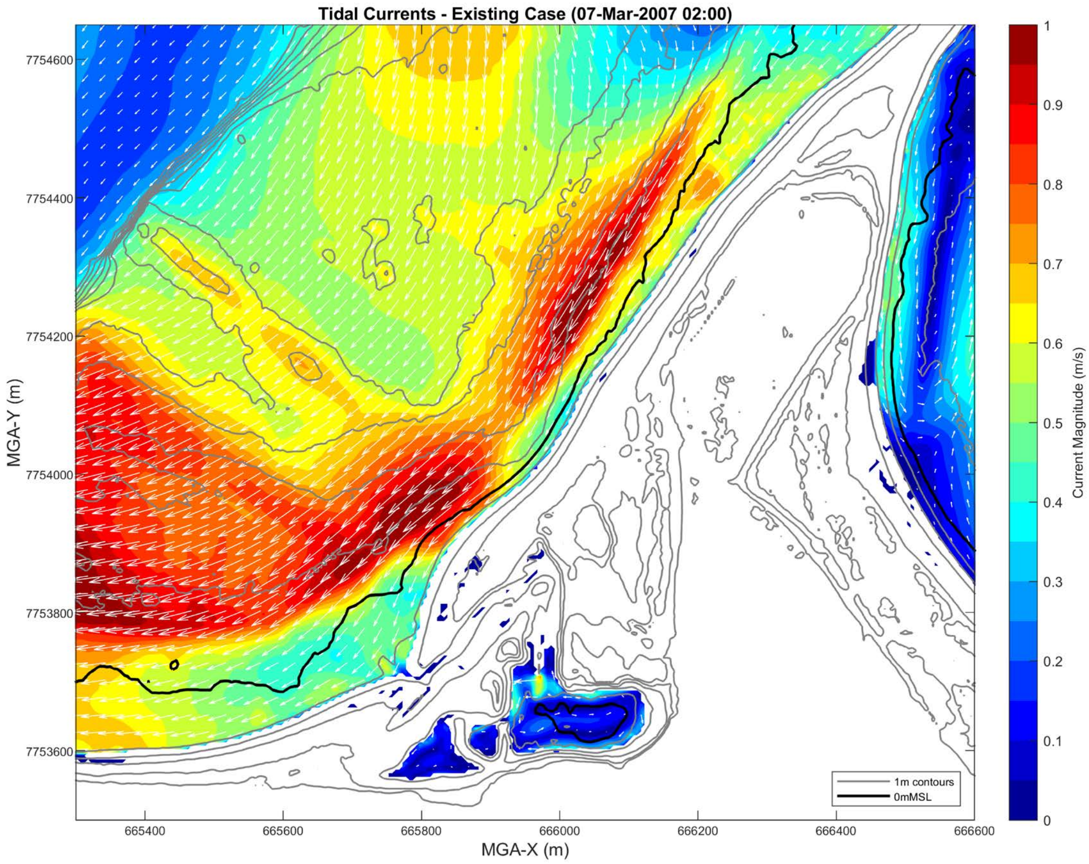


Figure 3.28: Peak Storm Induced Current Map (100-years ARI event) under Existing Conditions in the Vicinity of the Spoilbank Marina.

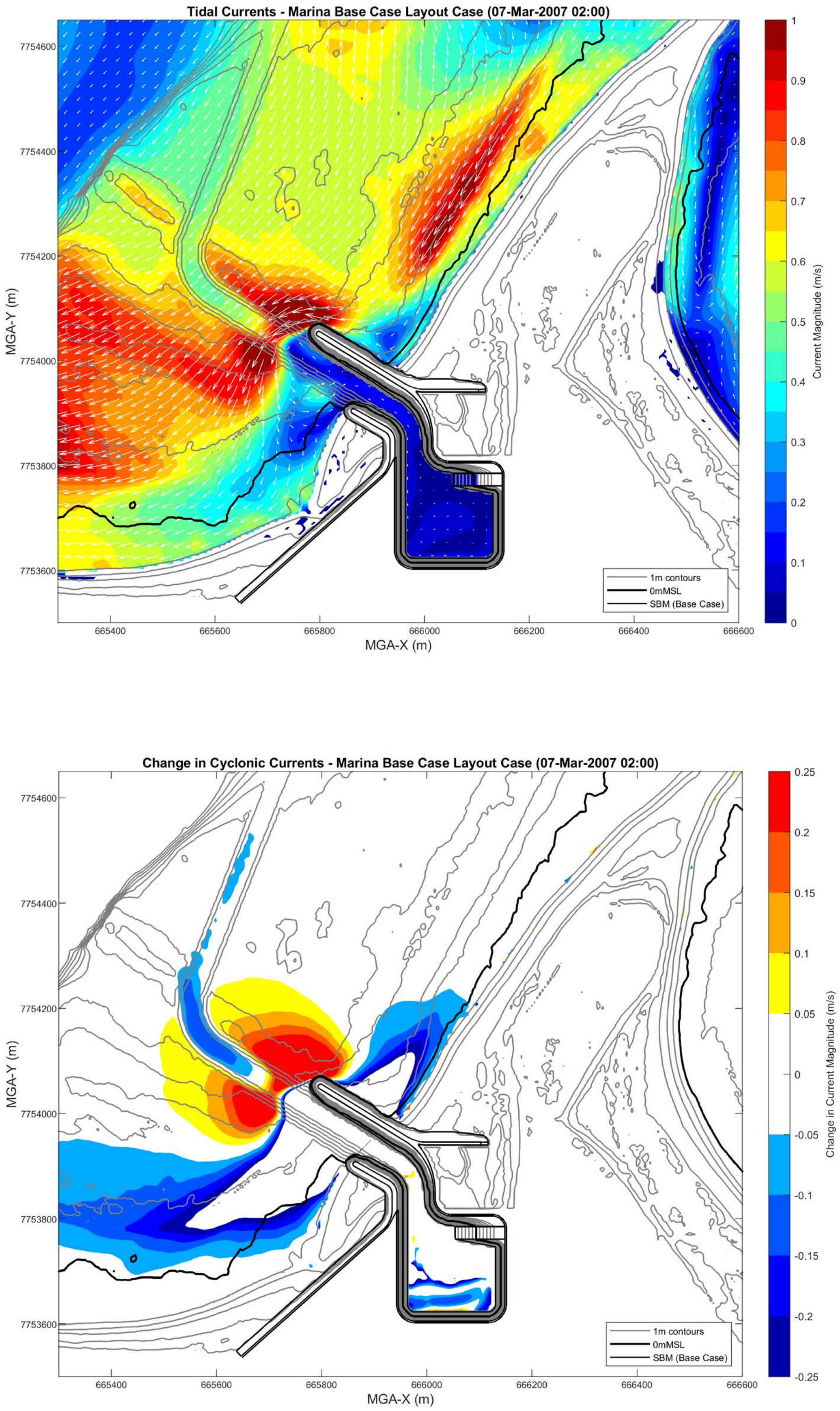
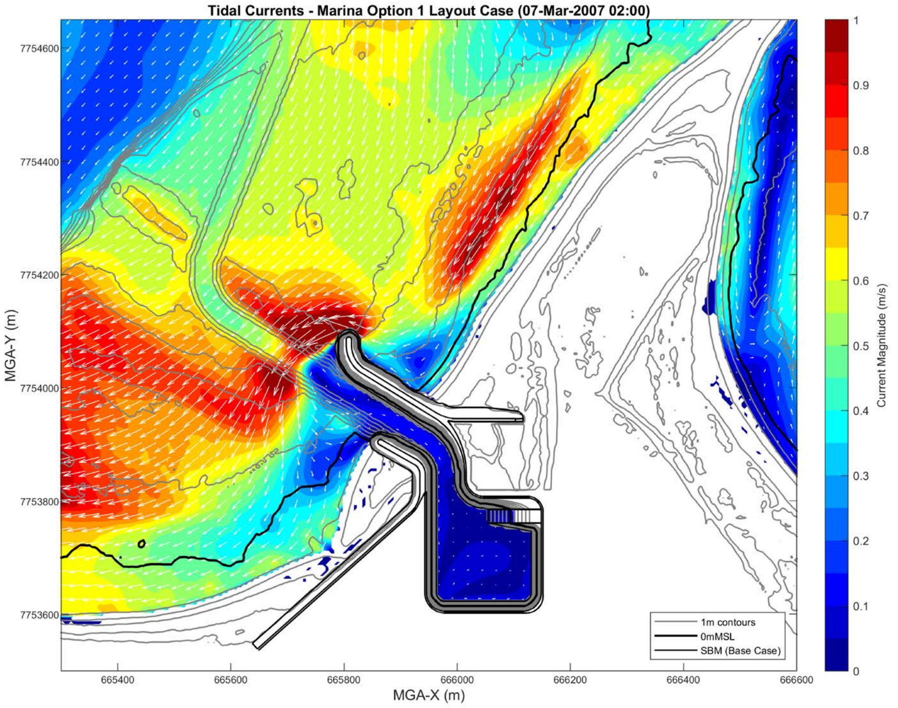


Figure 3.29: Peak Storm Induced (100-years ARI event) Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Base Case Marina Layout with Channel Option 1) in the Vicinity of the Spoilbank Marina.



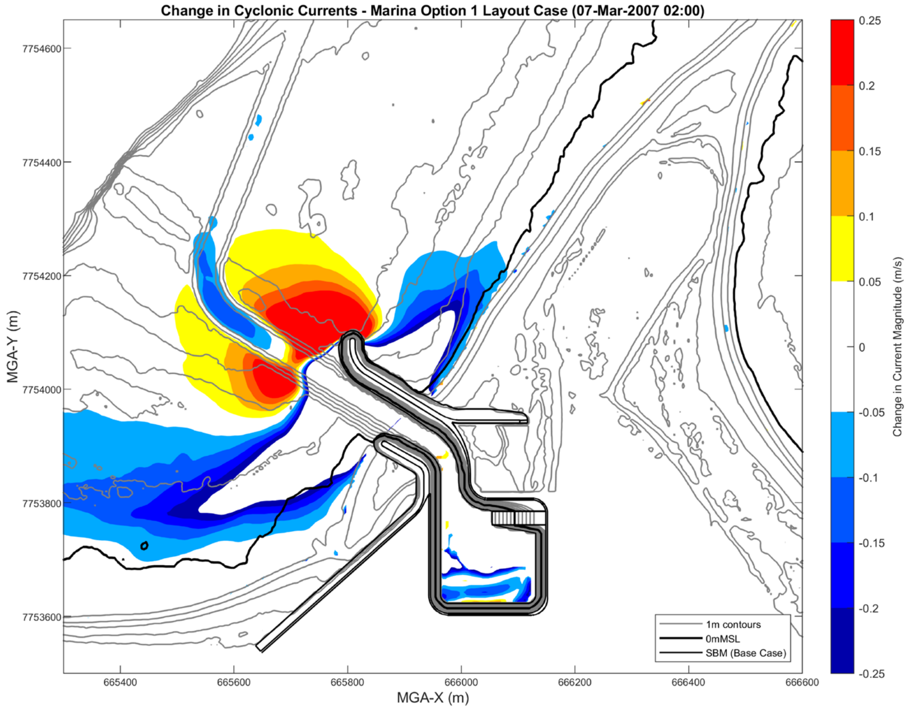
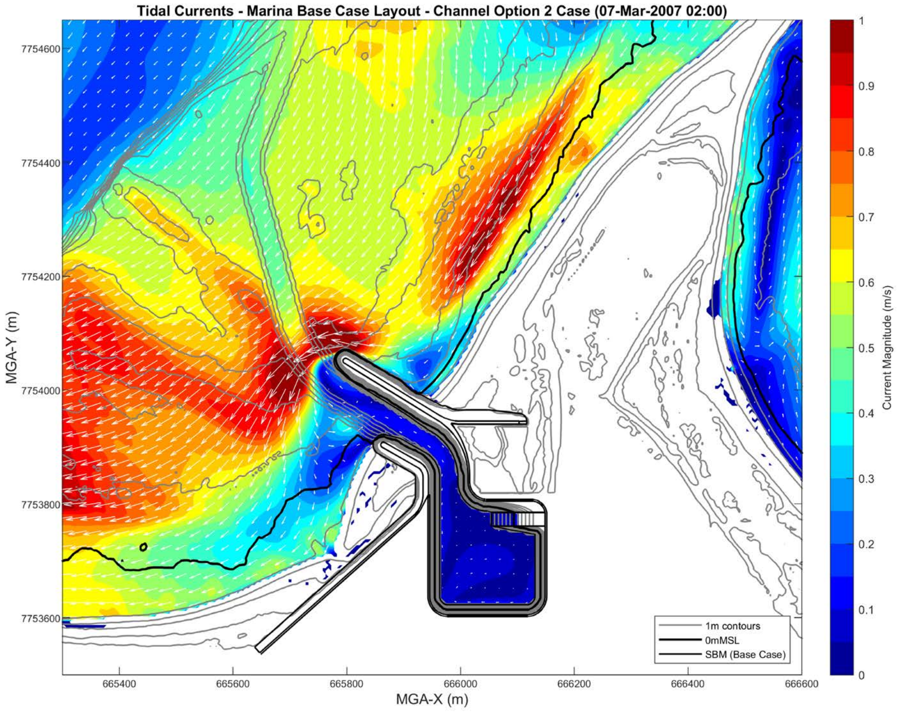


Figure 3.30: Peak Storm Induced (100-years ARI event) Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 1 Marina Layout with Channel Option 1) in the Vicinity of the Spoilbank Marina.



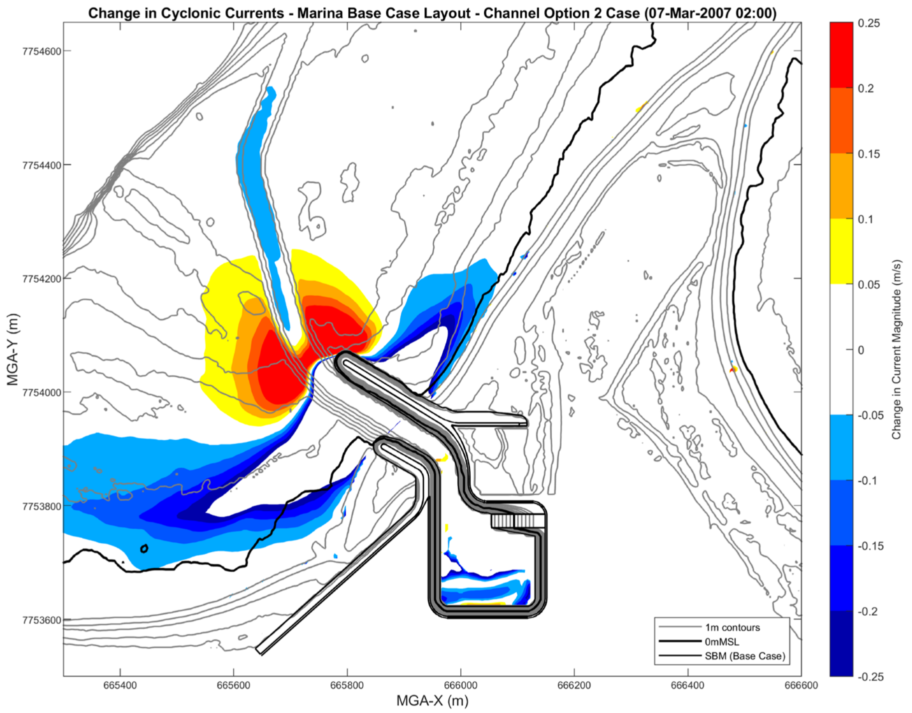
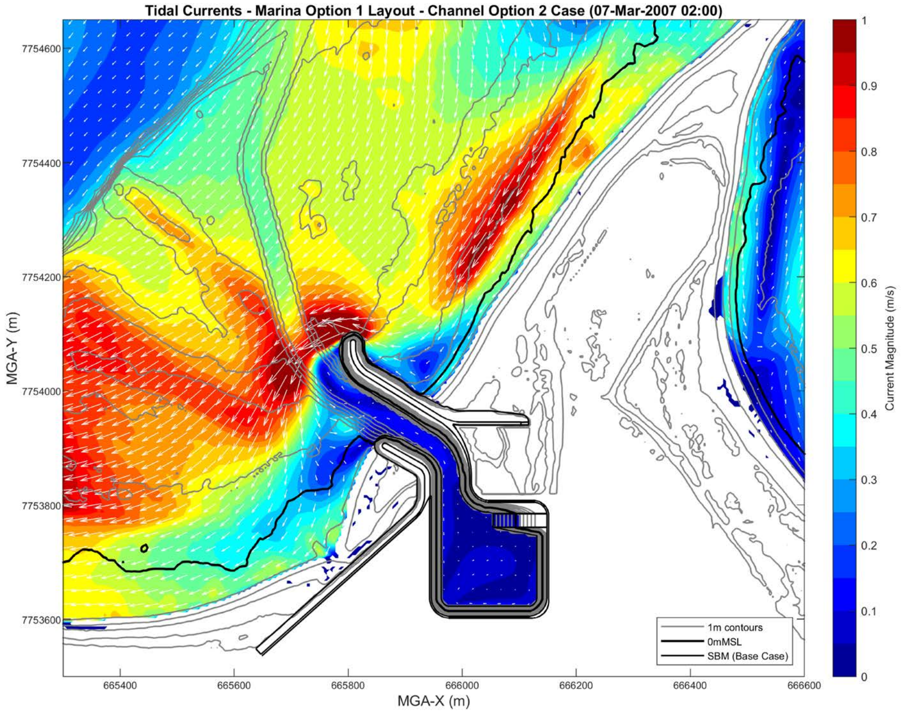


Figure 3.31: Peak Storm Induced (100-years ARI event) Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Base Case Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina.



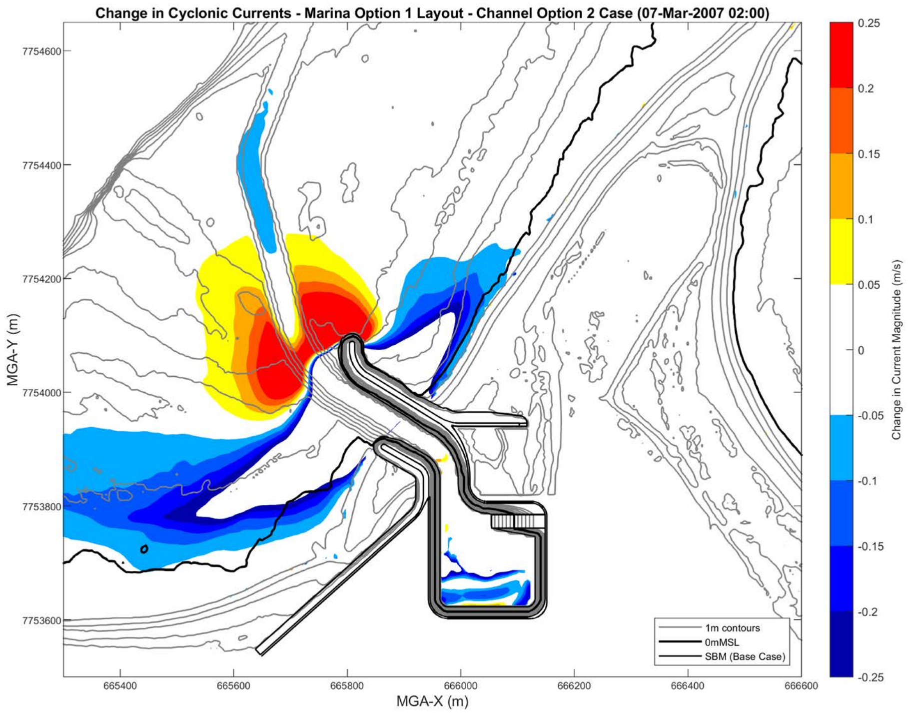
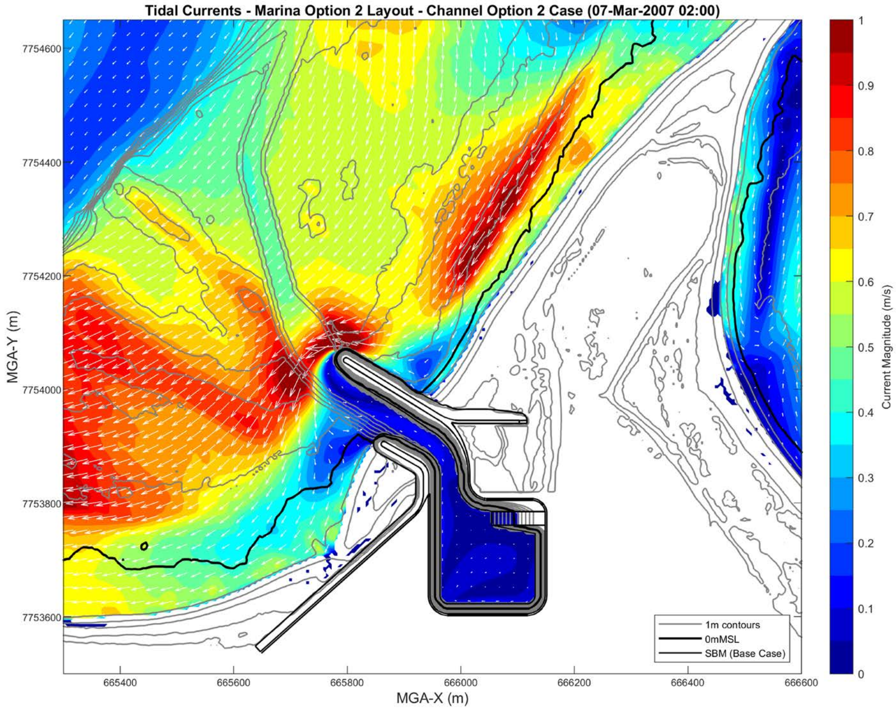


Figure 3.32: Peak Storm Induced (100-years ARI event) Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 1 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina.



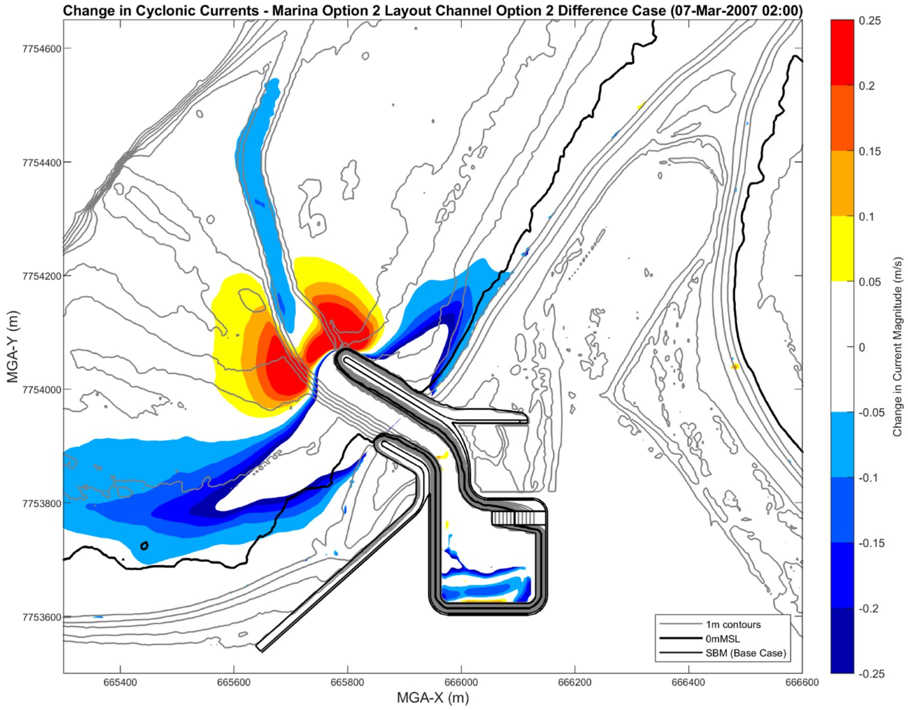


Figure 3.33: Peak Storm Induced (100-years ARI event) Current Map (top) and Current Magnitude Change (bottom) under Developed Conditions (Option 2 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina.

3.7.3 Water Levels

Water levels at Port Hedland are dominated by tides with the occasional addition of storm surge resulting from cyclonic events. The influence of the SBM on water levels was assessed by interrogation of the Delft3D simulations discussed in Section 3.7.1. Water level data was output from the model at the location of the Port Hedland tide gauge (at the PH2 berth inside the harbour), for a 28-day period spanning two typical spring-neap tide cycles, for both existing conditions (no marina) and with the inclusion of the proposed SBM. Comparison of the data, as shown in Figure 3.34, demonstrates that following development of the SBM, no discernible change in the tidal range or phasing will occur.

The effect of the proposed development was also quantified for storm conditions, as elevated water levels due to storm surge are a relatively frequent occurrence in the Port Hedland region. In order to investigate this effect, the coupled Delft3D model was run for the 100-years ARI design event. Comparison of the water level results at the DoTHD01 AWAC location, also shown in Figure 3.34, indicate that the total still water level (tides plus surge) are the same. It can therefore be concluded that the proposed SBM development will also have a negligible effect on cyclonic water levels across the area.

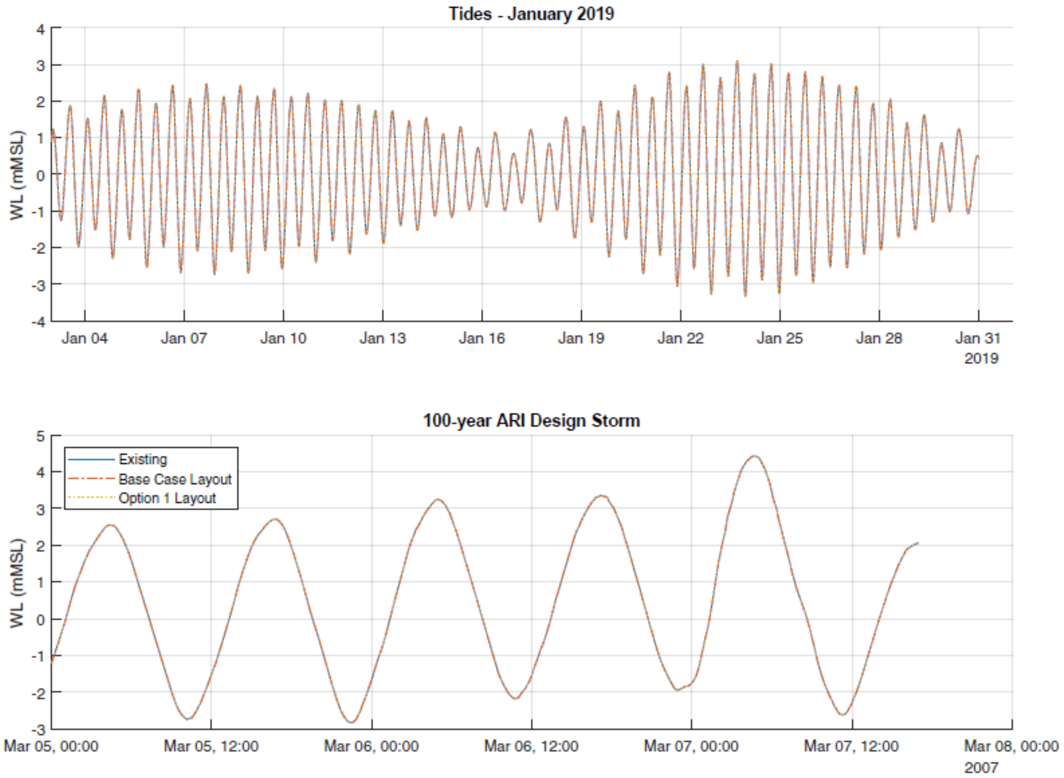


Figure 3.34: Water level comparisons between pre- and post- marina development cases for tides at the Port Hedland Tide Gauge (top) and storm surge at the DoTHD01 AWAC location (bottom).

Inspection of the peak spatial water level across the proposed marina development identified the potential for storm surge inundation around the eastern edge of the development's northern revetment. The extent on inundation at the peak of the 100-years ARI event is presented in Figure 3.35, noting that all land levels around the marina structures are based on the most recent survey (i.e. no fill or reclamation added to the model). During detailed design it is recommended that the length of this structure and tie in detail to existing land levels on the Spoilbank be reconsidered.

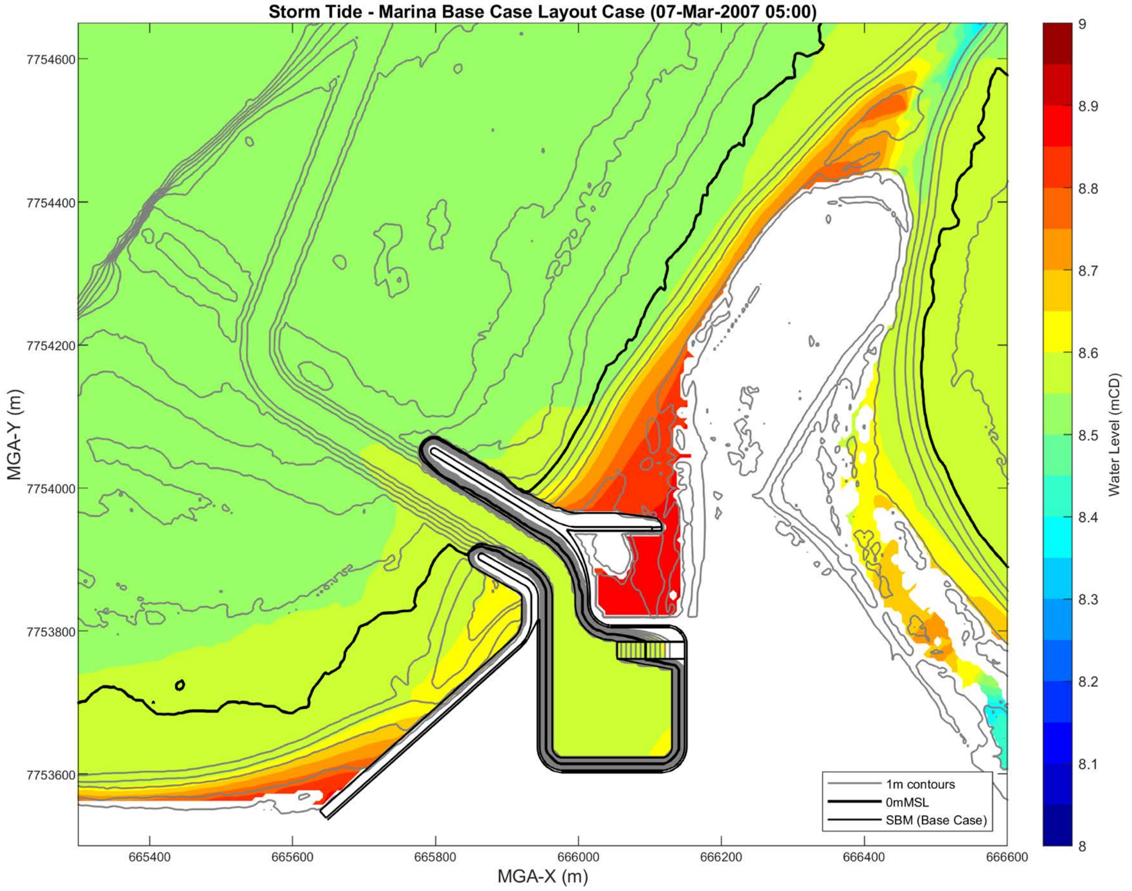


Figure 3.35: Storm Water Level Map showing wave setup at the shoreline and inundation around the Base Case Marina Layout under a 100-year ARI event.

3.8 Wave Condition Changes due to the Development

Wave conditions in the Port Hedland region are largely dominated by persistent north-westerly swell in the winter months and shorter period waves in the summer months which can be in excess of 2m (Hs). The largest waves experienced along the coast in the region of Port Hedland generally occur between November and April and are associated with tropical cyclone systems. Given that the Pilbara region is highly prone to cyclonic activity, wave conditions at the site can be divided into two distinct categories; ambient and cyclonic.

Wave propagation outside the proposed SBM footprint is a key factor in the seabed and shoreline evolution of the area and a change to wave conditions may manifest in broader coastal process impacts. To assess the influence of the proposed marina on the wave climate in its vicinity, two wave model systems were employed to spatially quantify wave conditions for both cyclonic and ambient conditions.

The first was the spectral wave model (SWAN), as part of the coupled hydrodynamic and wave model described in Section 3.6, that was used to investigate wave generation and propagation to and into the entrance of the SBM. However, spectral wave models do not explicitly calculate certain wave processes, such as diffraction and reflections. Given the complex bathymetric features of the area, including the Spoilbank landmass and the Goldsworthy navigation channel, a phase-resolving wave model (MIKE21-BW) was developed to provide confidence in the outputs from the spectral wave model.

3.8.1 Ambient Conditions

Ambient wave conditions are being assessed as part of the sediment transport study that is currently in progress. This section will be updated once those investigations are completed.

3.8.2 Cyclonic Conditions

Cyclonic wave conditions were determined for Average Recurrence Intervals between 20 and 500-years based on a comprehensive modelling study of the site (see Section 4). From this, a 100-years ARI design storm was identified, and this was used to assess pre- and post-marina development wave conditions in the coupled Delft3D FWF model. The model was initially run with existing conditions (i.e. no marina development) and the resulting peak significant wave height map is shown in the Figure 3.36.

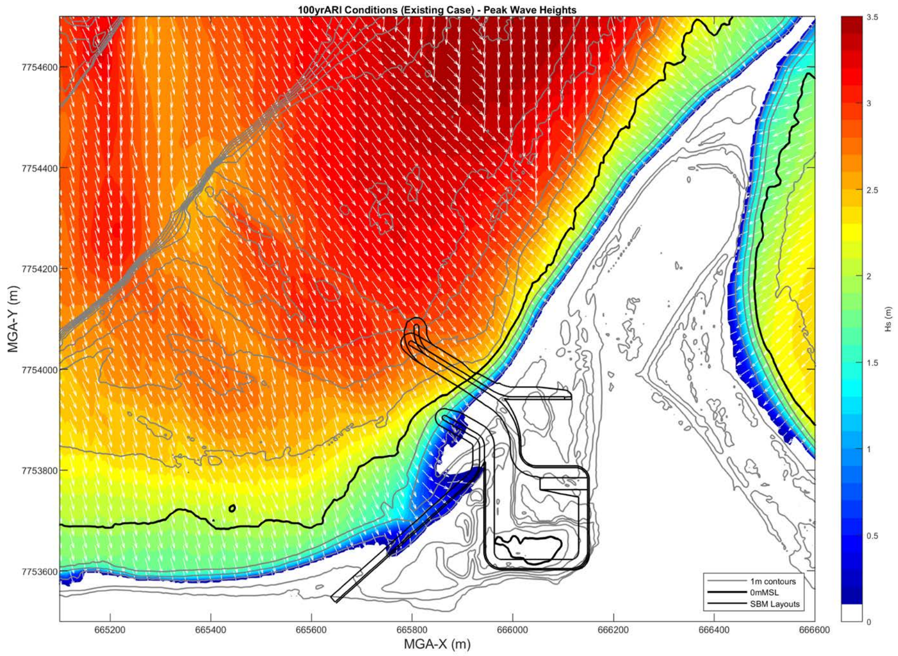


Figure 3.36: 100-years ARI Peak Wave Height and Direction Map for Existing Conditions in the Vicinity of the Spoilbank Marina

The following set of figures present the modelled current fields for the five marina layout and channel options for the 100-years ARI condition (same timestep as existing case presentation above) along with the difference maps that identify the magnitude change in wave height as a result of the development.

- Figure 3.37 presents the Base Case layout with Option 1 channel;
- Figure 3.38 presents the Option 1 layout with Option 1 channel;
- Figure 3.39 presents the Base Case layout with Option 2 channel;
- Figure 3.40 presents the Option 1 layout with Option 2 channel;
- Figure 3.41 presents the Option 2 layout with Option 2 channel.

Generally, changes to the wave climate are localised with the most pronounced change being a reduction in wave heights in the lee of the breakwater structures. Further away from the SBM entrance the influence of the dredged entrance channel is evident with both entrance channel options imparting a reduction in the incoming wave conditions. This is most evident for the Option 2 channel, indicating the sensitivity of this channel refraction effect to the relative alignment of the channel to the incoming waves. Being more aligned to incoming waves, the Option 1 channel imparts a small increase in the waves along the northern channel shoulder due to channel refraction.

Wave penetration through the entrance channel and into the basin is described by the spectral wave model resulting in conditions up to 0.2m (Hs). The reliability of this estimate of wave penetration is further discussed in the context of a phase resolving model (MIKE21-BW) in the section below.

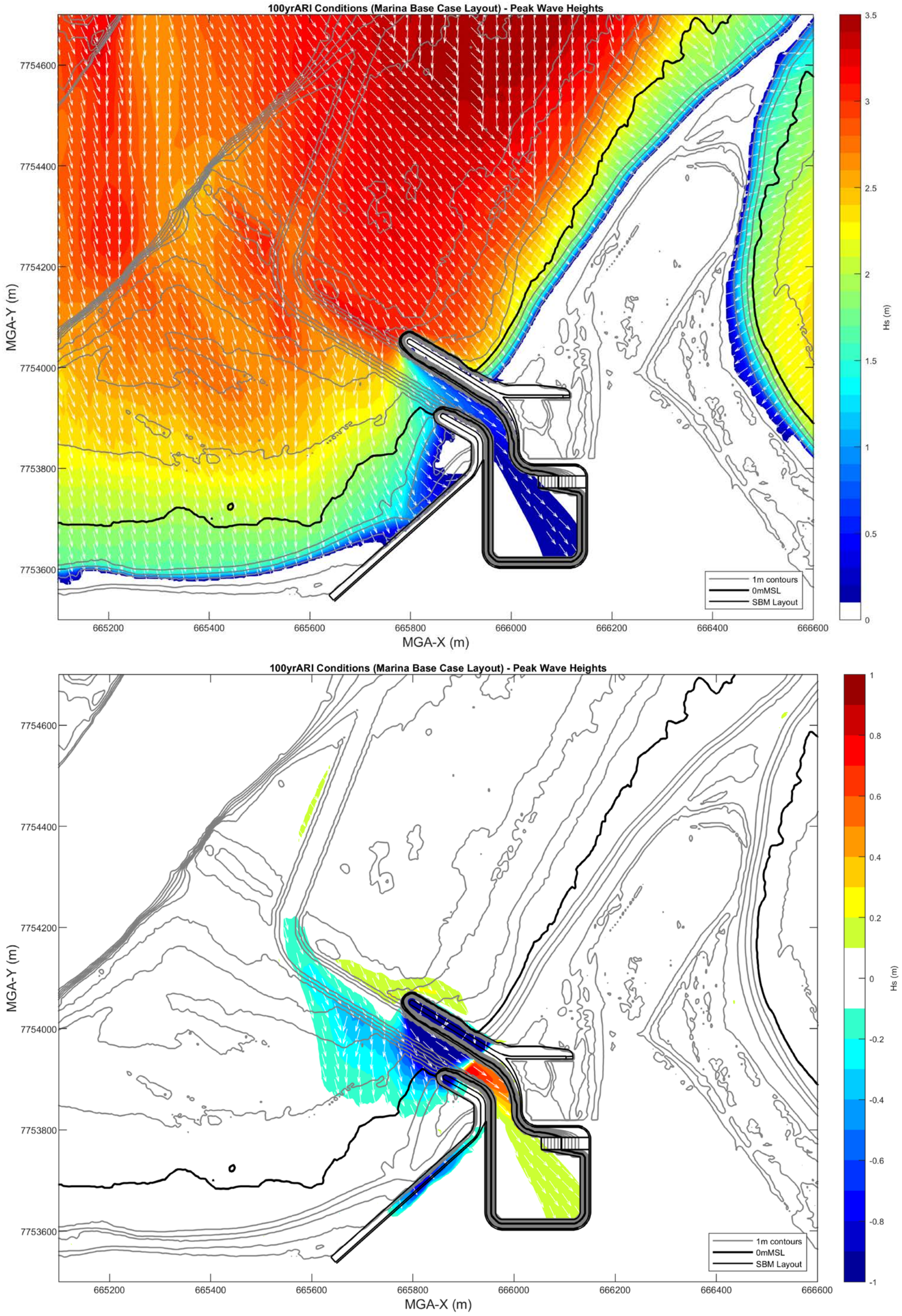


Figure 3.37: 100-years ARI Peak Wave Height and Direction Map (top) and Wave Height Change (bottom) under Developed Conditions (Base Case Marina Layout) in the Vicinity of the Spoilbank Marina

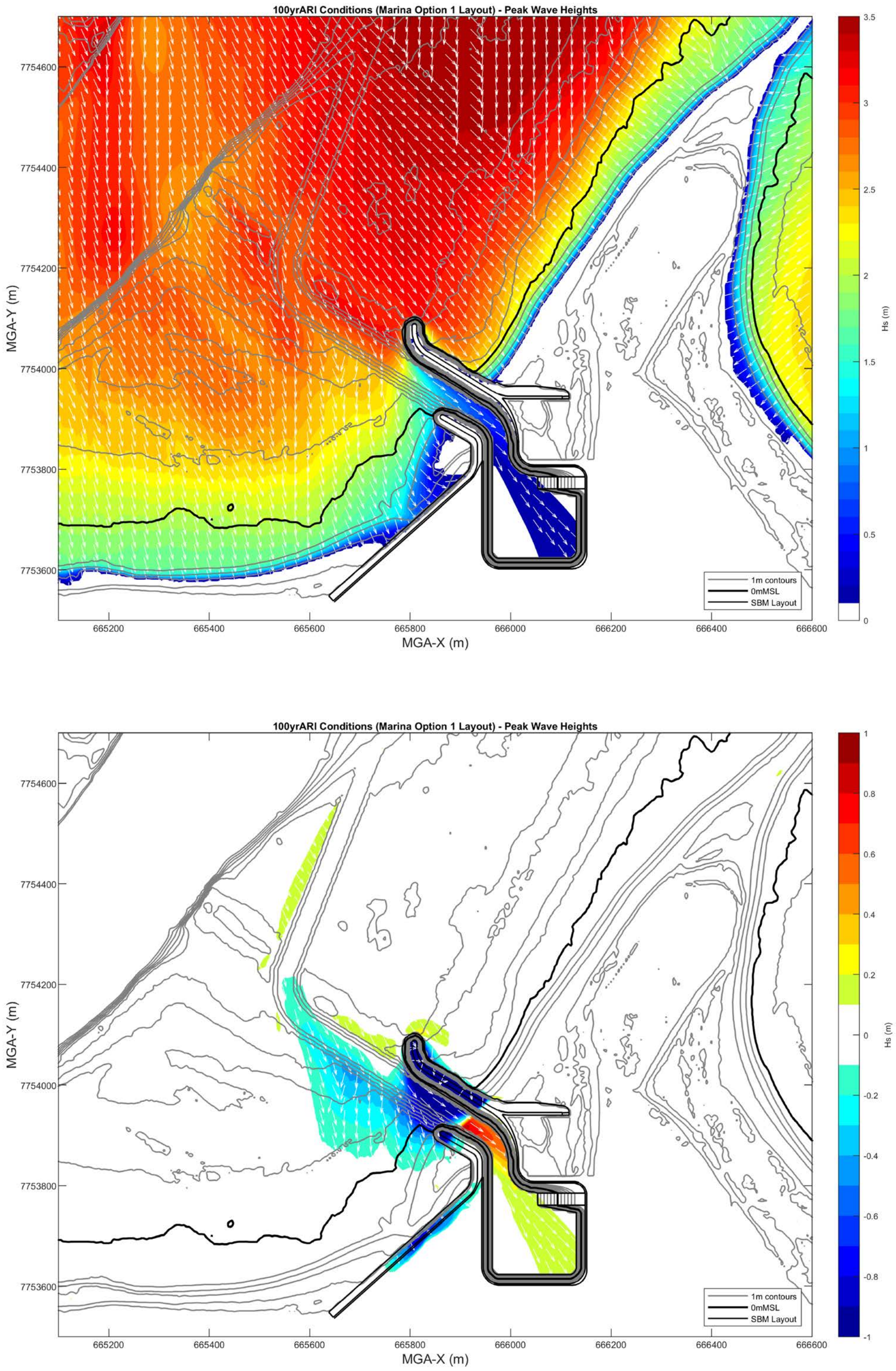
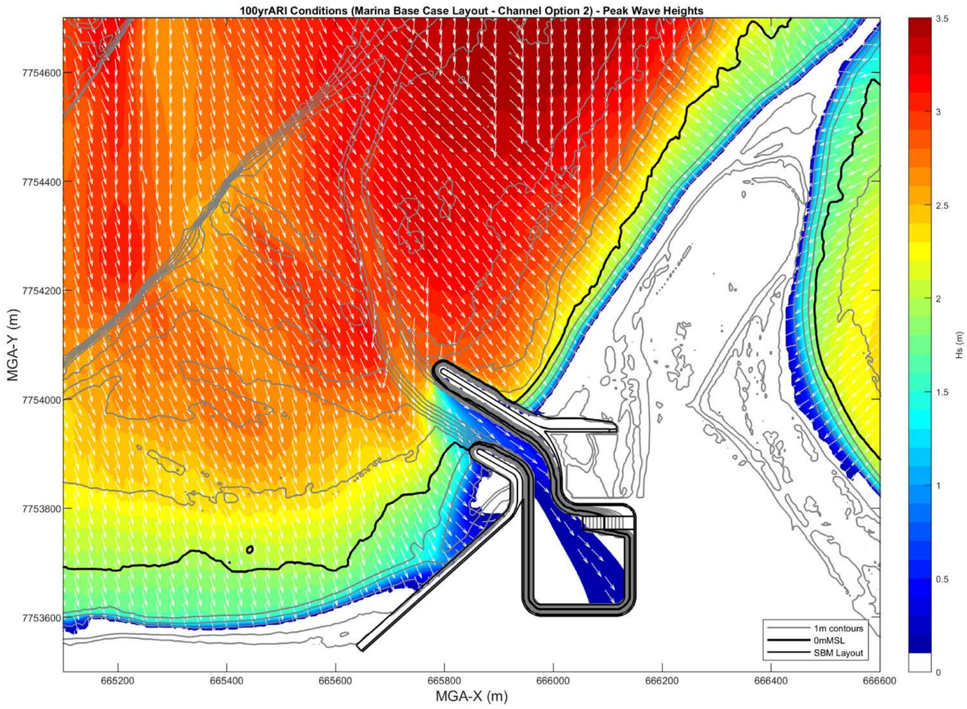


Figure 3.38: 100-years ARI Peak Wave Height and Direction Map (top) and Wave Height Change (bottom) under Developed Conditions (Option 1 Marina Layout) in the Vicinity of the Spoilbank Marina



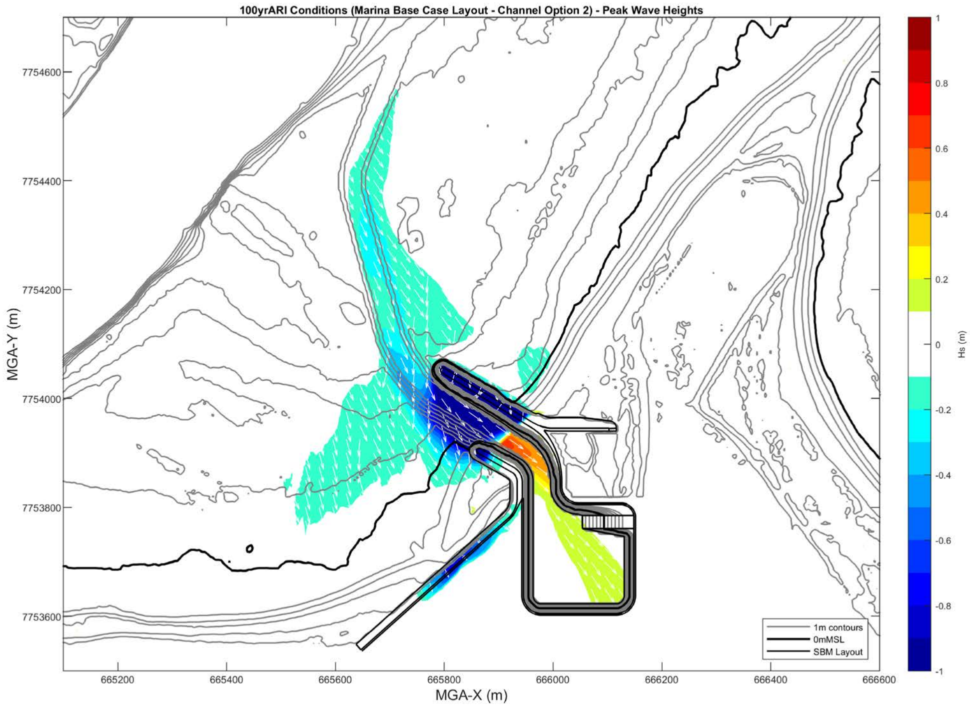


Figure 3.39: 100-years ARI Peak Wave Height and Direction Map (top) and Wave Height Change (bottom) under Developed Conditions (Base Case Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina

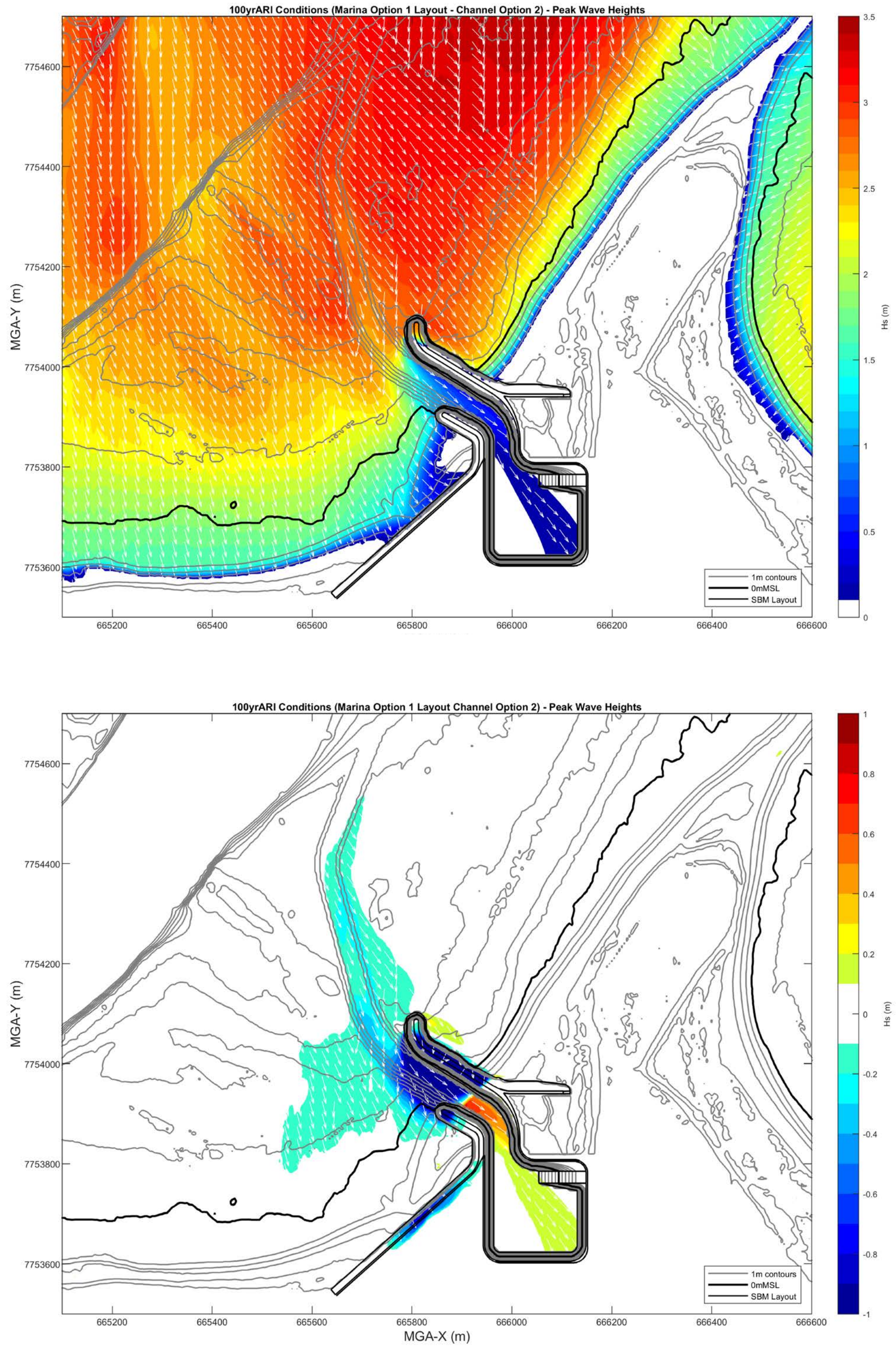
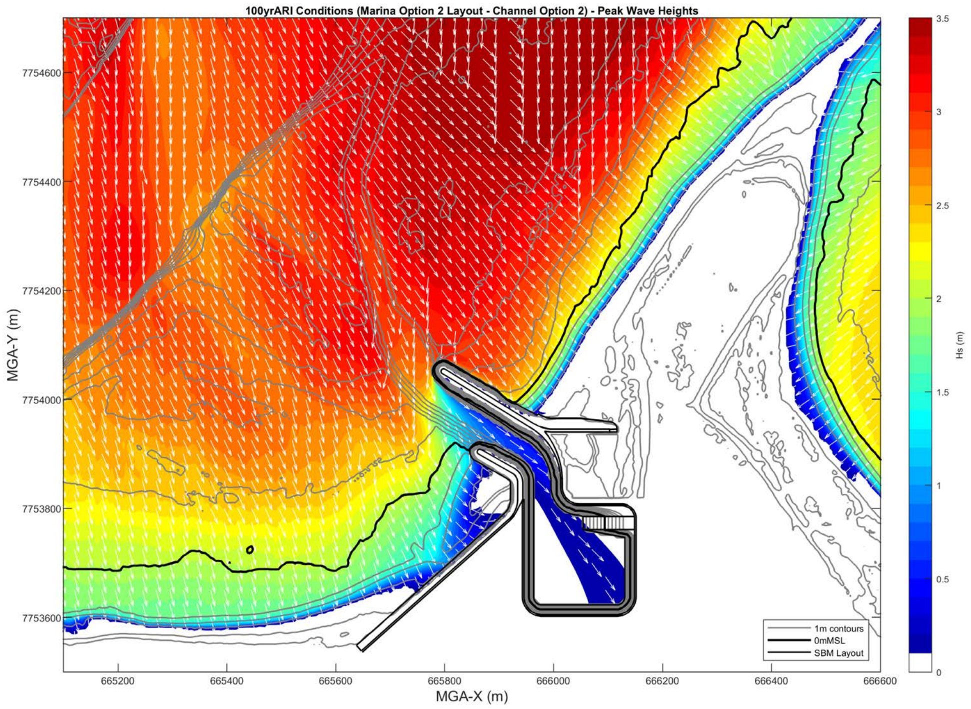


Figure 3.40: 100-years ARI Peak Wave Height and Direction Map (top) and Wave Height Change (bottom) under Developed Conditions (Option 1 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina



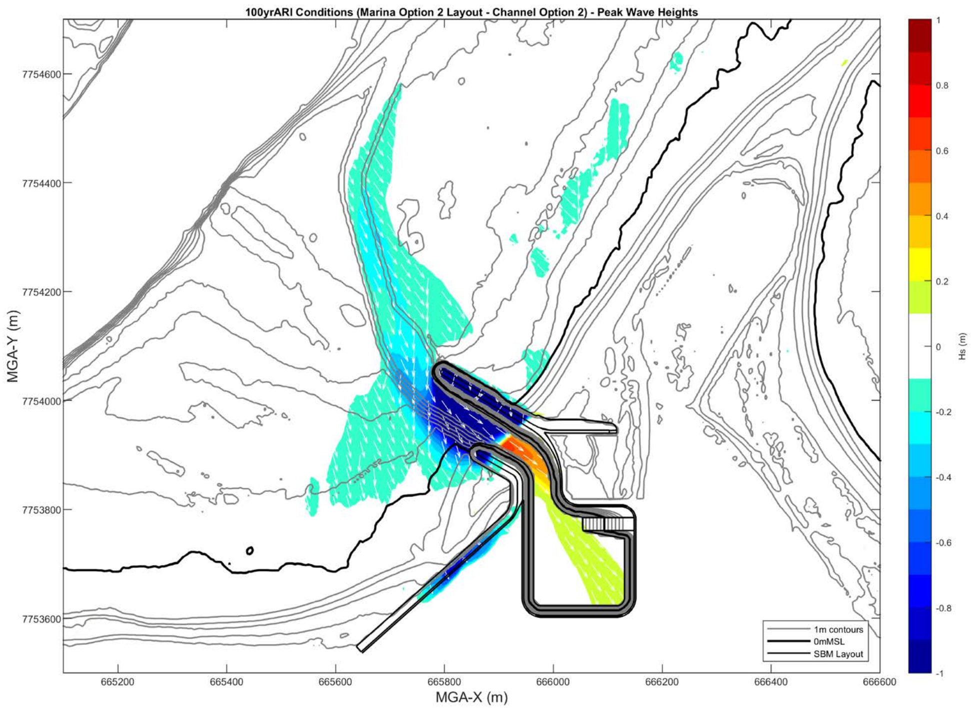


Figure 3.41: 100-years ARI Peak Wave Height and Direction Map (top) and Wave Height Change (bottom) under Developed Conditions (Option 2 Marina Layout with Channel Option 2) in the Vicinity of the Spoilbank Marina

3.9 Cyclonic Conditions – Phase Resolving Modelling

A phase-resolving model was used to examine wave propagation and transformation of the offshore 100yr ARI conditions through the nearshore region and marina entrance for each marina layout case. The MIKE21BW model, developed by DHI, is a phase resolving model suited to examining the wave transformation across the complex bathymetry of the Port Hedland offshore areas where reflection, diffraction and refraction processes are all occurring. The transformation of extreme waves from offshore to the SBM including wave interaction with the Goldsworthy Channel and the channel batters of the SBM entrance channel have been examined to assess wave conditions at the SBM structures. It is noted that the model does not include wind effects and is purely being driven by the offshore cyclonic condition (as defined by Delft3D FWF modelling).

The MIKE21-BW model was forced with offshore wave conditions that generated a 100-year ARI cyclonic wave condition at the SBM location. This extreme cyclonic condition was simulated with a jointly occurring 100-years ARI water level of 8.6m CD. Nearshore wave conditions are highly dependent on water level and such a high-water level is required for larger wave conditions to occur. A peak period (Tp) of 9.5s and directional wave conditions at the boundary were applied from a wave direction of 340º TN with directional spreading around the peak direction of 20 degrees. This wave direction is to the western limit of the peak wave conditions derived from the 100-year ARI event set and have the greatest potential for wave penetration into the SBM entrance due to the alignment with the entrance channel orientation.

The modelled wave conditions for each of the cases is presented in Figure 3.42 for the entire model domain, and in Figure 3.43 covering the SBM entrance area. The effect of the Goldsworthy Channel is evident, with incoming waves reflected and refracted away from the channel. Wave energy transferred across the channel is greatly reduced by the channel effect. Closer to the SBM location, a secondary smaller scale channel effect is noted particularly for the Option 2 alignment. For both the base case and Option 1 layouts the structures offer good protection from the swell wave conditions and propagation through the entrance channel into the basin is minimal.

It is highlighted again that the MIKE21-BW model does not include wind generation over the model domain, which the Delft3D model indicates is the dominant contributor to peak wave conditions at the SBM entrance location under extreme cyclone events. However, the MIKE21-BW confirms the observation from the spectral wave modelling (FWF/SWAN) that channel refraction processes across the Goldsworthy and SBM entrance channel are significant. For comparison a spectral model (SWAN) was established over the same extent as the MIKE21-BW model and forced with the same offshore wave boundary conditions, with no winds applied. The resulting peak wave maps for both channel options are shown in Figure 3.44. The results between the two models are comparable with the influence of the channels evident in both models. However, the channel interaction appears stronger in the MIKE21-BW model, than the spectral wave model results, providing a level of confidence that sheltering from the channels is not being over-estimated in the FWF/SWAN models.

Therefore, and with consideration of the model validations presented in Section 3.6.2, the results from the coupled hydrodynamic and spectral wave model are considered suitable for the definition of design waves at the SBM location.

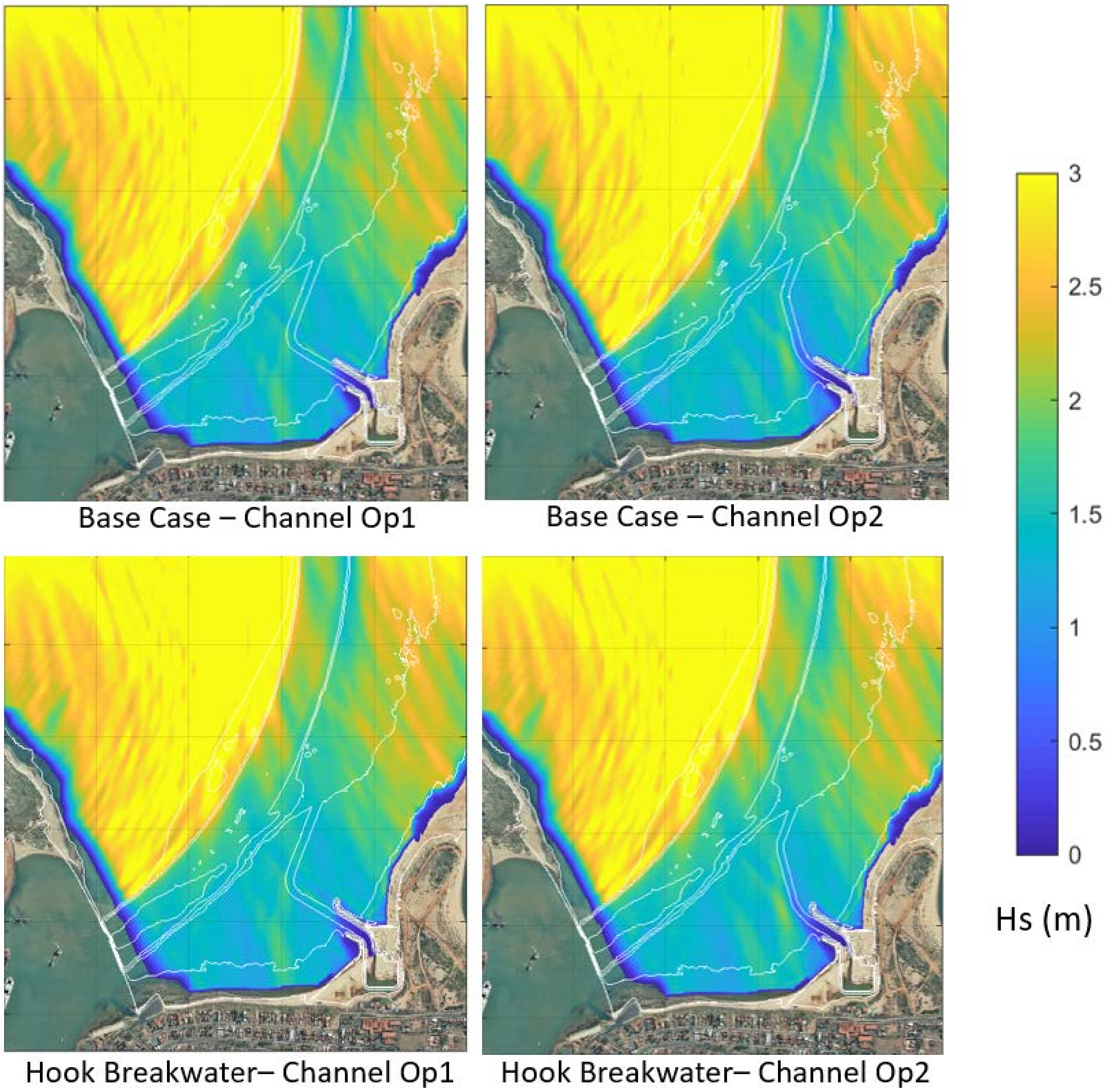


Figure 3.42: Phase-resolving wave transformation maps of the offshore 100-year ARI condition over the extent of the MIKE21-BW model domain. Wave conditions exclude the contribution of locally generated sea conditions.

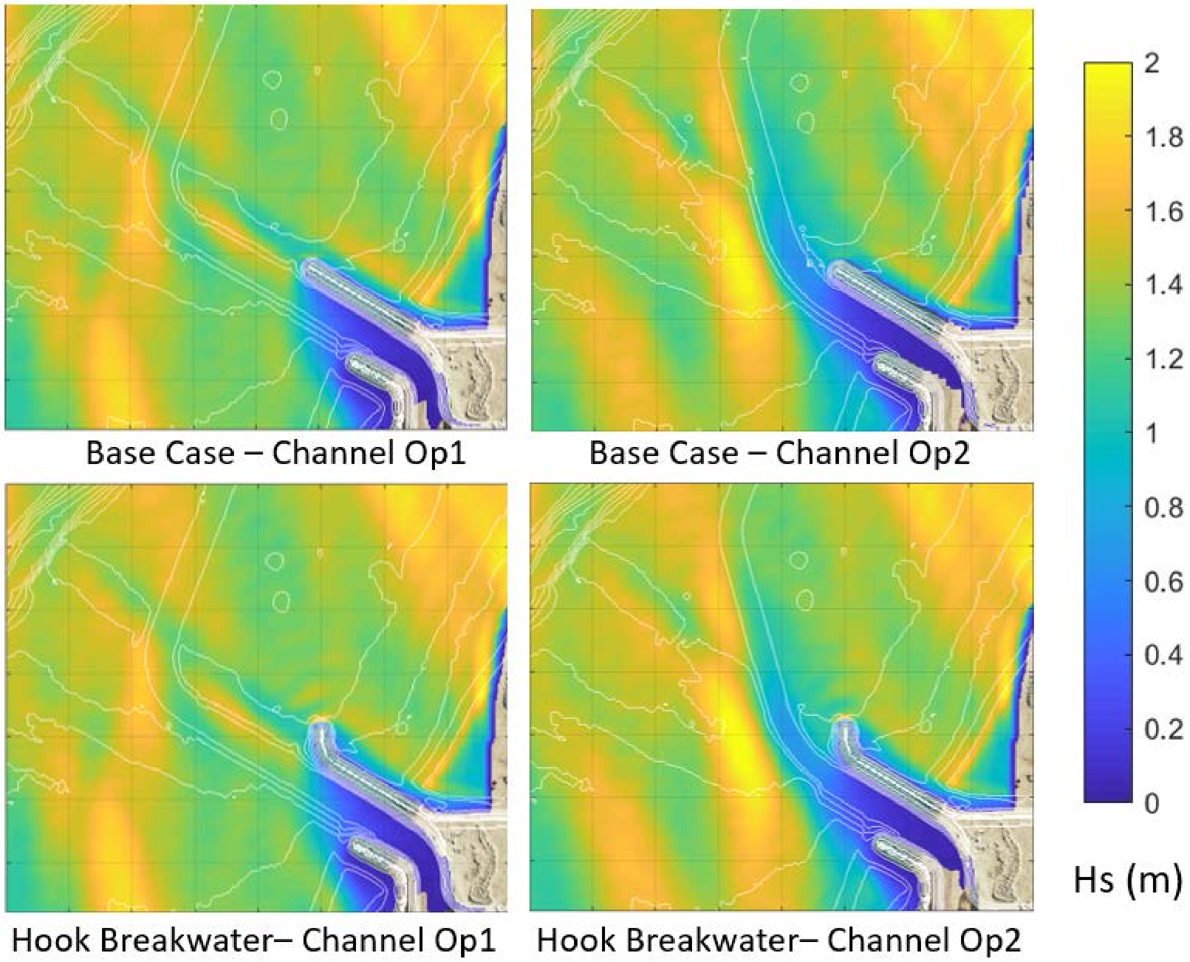


Figure 3.43: Phase-resolving wave transformation maps of the offshore 100-year ARI condition over the SBM entrance and channel areas. Wave conditions exclude the contribution of locally generated sea conditions.

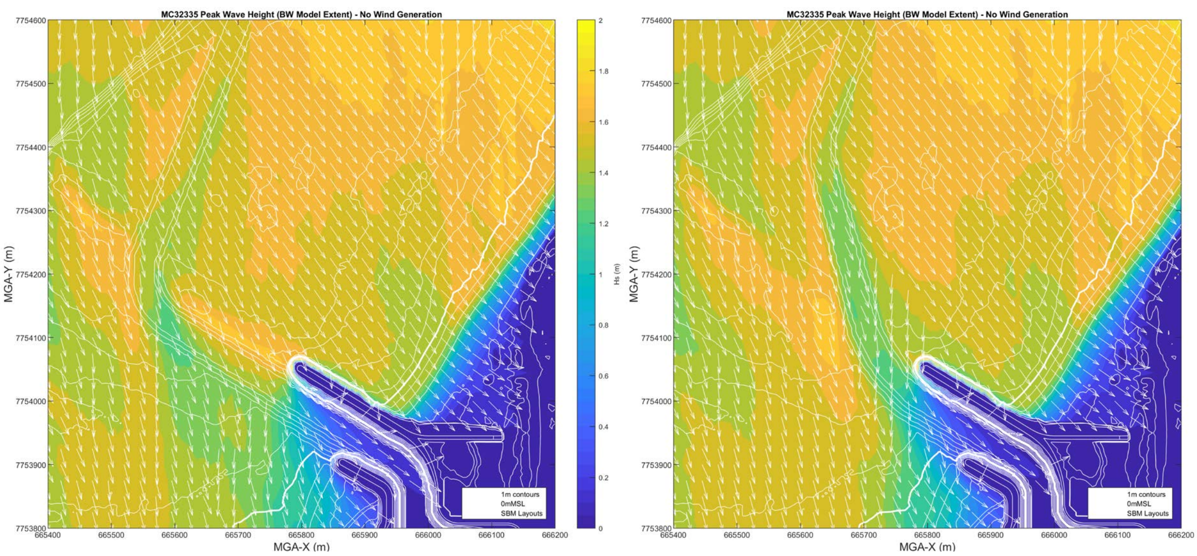


Figure 3.44: Spectral wave transformation maps of the offshore 100-year ARI condition over the SBM entrance and channel areas. Wave conditions exclude the contribution of locally generated sea conditions.

4. Metocean Design Criteria

Metocean design criteria are presented for following parameters:

- Cyclonic winds;
- Cyclonic water levels including storm surge, background residual and astronomical tide;
- Cyclonic waves; and
- Coastal inundation including wave run-up.
- Cyclonic water levels and waves for a sea level rise condition of +0.39m (50-year planning period)

At Port Hedland, design coastal wave, water level and wind conditions are highly correlated, and the following criteria should be considered jointly. That is, the design values for winds, water levels, waves and currents should be applied concurrently for the purposes of design.

Metocean design criteria have been derived spatially across the marina development for 12 metocean zones, as defined in Figure 4.1, for Average Recurrence Intervals (ARIs) of 1, 5, 20, 100 and 500-years. Values in this section are presented for the Northern Breakwater end (Metocean Zone 1), with criteria for all zones presented in Appendix C.

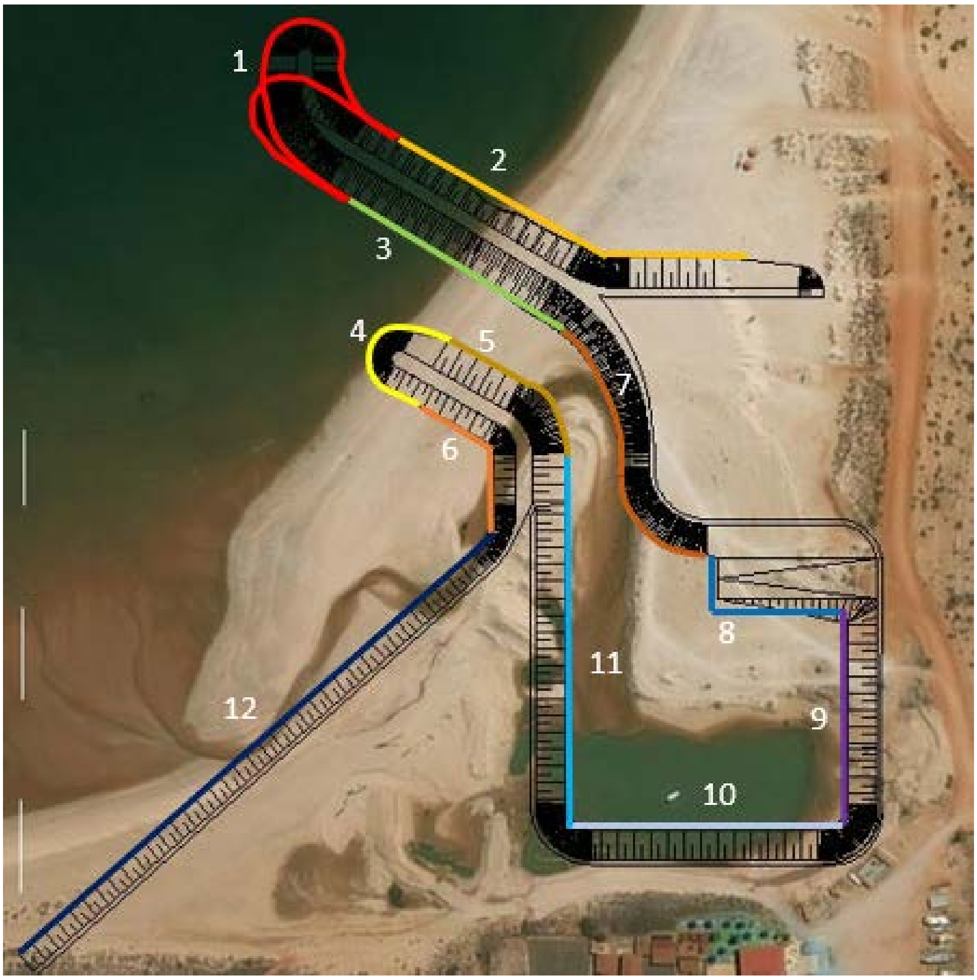


Figure 4.1: Definition of Metocean Zones for Spatial Metocean Design Criteria

4.1 Metocean Dataset

To derive extreme metocean design conditions out to the 500-year ARI for the Port Hedland SBM project, a suitable cyclone event set that extends the historical record with simulated events using a stochastic-based modelling approach, thereby capturing peak water level and wave conditions over a long period, was required. Baird's Australian Tropical Cyclone Database, as presented in Section 3.2, was used to identify suitable design storm events for metocean criteria development.

In addition to cyclone tracks and wind fields, the database also includes modelled storm water levels for all 28,096 coastal events (i.e. events that pass into the northern WA region and within 200km of the coast), generated from shelf scale hydrodynamic modelling using Baird's calibrated Delft-FM model of the Northwest Shelf (see Section 3.4). However, simulation of this event set at the required spatial resolutions for hydrodynamics and waves at the SBM site was not computationally feasible within this study scope, hence a design storm approach was undertaken by identifying suitable Monte Carlo events from the existing database. The selected event set was subsequently modelled using the high-resolution site specific hydrodynamic and wave models for this study (see model setups in Section 3.6). An envelope of the resulting metocean conditions was then adopted to define metocean criteria at the 20, 100 and 500-year ARIs. Adopting a design storm approach, rather than modelling the full Monte Carlo event set, has the potential to mischaracterise the design events, however at the SBM site wave conditions are highly correlated with water level (water depth) which is a parameter that was available for the full Monte Carlo storm set. An event selection approach was then needed to ensure that key variables affecting nearshore wave heights at the SBM were considered, such as offshore wave direction and cyclone track approach. The event selection rationale is presented in the Sections below.

Design criteria at lower return periods of 1 and 5-years ARI were also requested for design tasks. The Monte Carlo dataset of cyclone tracks and windfields is not a suitable dataset to define lower return period values (<20year ARI) as it will exclude non-cyclonic conditions that may contribute to the event population at lower recurrence intervals. As such the available measured data was utilised to complete an extreme value analysis to define the 1 and 5-years ARI winds, waves and water levels. The EVA from the measured data was cross checked against the 20, 100, & 500-year ARI conditions, derived from the Monte Carlo dataset, to ensure consistency across the return period space.

4.1.1 Event Selection

Given that design coastal wave, water level and wind conditions are highly correlated at Port Hedland, a targeted event set was identified from the larger database, that consisted of events representative of the 20, 100 and 500-year ARI storm water level conditions. A total of 30 events (10 at each recurrence interval) were selected, so as to adequately capture and investigate sensitivities around each design condition (e.g. direction of cyclone approach, variation in peak wind speeds etc.).

Event selection started with identification of events that had near to the target recurrence interval total water level (e.g. 100-years ARI water level), however also made consideration of the cyclone track approach. The final selection of an event subset of 10 storms at each recurrence interval, ensured that tracks approaching from the NE were not dominating the event set and a realistic range of track approaches were covered. Figure 4.2 presents the 10 selected event tracks at each recurrence interval. It is noted that the full range of track alignments are being captured by the event selection, particularly at the 100 and 500-year ARI level, and hence sensitivity to track approach is inherently captured in the selected event sets (further discussed in Section 4.3.3). For reference, the track of TC Veronica is also included in Figure 4.2, whose track alignment (approach angle to the coast) is comparable to the NNE tracks from the Monte Carlo model.

A confirmation of the event selection was also completed following simulation of wave conditions with the shelf and local scale wave models by consideration of offshore wave heights at Beacon 15/16 and confirming with the selected events at each return period were comparable to the return period conditions from the Beacon 15/16 record. A summary of the 100-year ARI event set wave heights at Beacon 15/16 is summarised in Table 4.4, which indicates that peak modelled wave heights for 7 of the 10 events are within 0.3m of the 100-years ARI wave height of 7.1m (Hs) at Beacon 15/16.

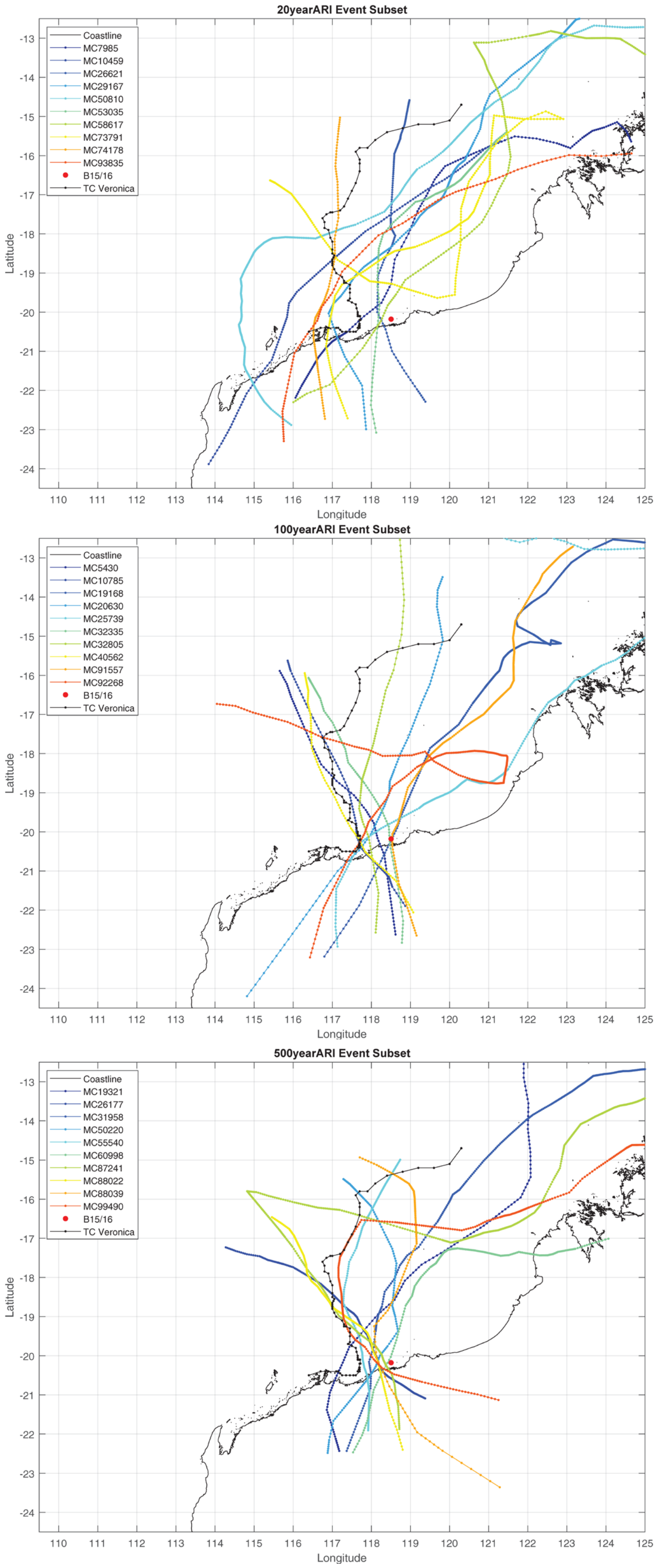


Figure 4.2: Design Cyclone Event Set Tracks for 20-years ARI (top), 100-years ARI (middle) and 500-years ARI (bottom). Port Hedland (B15/16) is identified as a red dot.

4.2 Cyclonic Winds

A range of cyclonic wind data sources are available including long-term measured data from Port Hedland Airport, synthetic datasets and structural design codes (AS/NZS 1170.2:2011). The SBM is located at the open coast and for extreme cyclone events that generate large surge and waves at the site, the cyclone winds will have minimal influence from land interaction. To this end, the ‘over-water’ synthetic wind data set, derived from the Monte Carlo storm dataset described in Section 3.2, has been adopted to define cyclonic winds for the SBM. The extreme wind event set has a sample population of 4,200 extreme cyclone events that tracked within 150km of Port Hedland with a central pressure of less than 980 hPa. Table 4.1 presents the over-water omni-directional wind speed conditions at the site (10-minute average, 10 m elevation).

Table 4.1: Over-water Extreme Cyclonic Wind Speeds, 10min average, 10m elevation, Omni-directional

ARI (years)	Wind Speed (m/s)
1	27.3
5	33.5
20	37.9
100	42.1
500	48.5

4.3 Cyclonic Water Level and Wave Conditions

Cyclonic water level and wave conditions were derived from site specific modelling of events from the Monte Carlo event set (see Section 3.2). Extreme total still water levels were defined from modelling an extended event set of 28,096 events with Baird’s shelf scale DefltFM model. The modelling includes dynamic modelling of astronomical tide and storm surge from spatial and temporal varying wind and pressure forcing but does not include wave and is therefore exclusive of wave setup.

High resolution modelling of a sub-set of representative cyclone cases at each ARI, as defined in Section 4.1.1, was then completed with the local scale coupled hydrodynamic and wave model of the Port Hedland Spoilbank (see Section 3.6) to determine cyclonic wave criteria for the SBM. This modelling took boundary conditions from the shelf scale hydrodynamic and wave models and included dynamic modelling of astronomical tide and storm surge from spatial and temporal varying wind and pressure forcing and the influence of wave radiation stresses on wave setup at the shoreline. Estimates of wave setup for each recurrence interval were estimated from the coupled model and applied to the extreme still water level estimates derived from the DelftFM model.

4.3.1 Water Levels

Design water levels for the western shoreline of the Spoilbank are presented in Table 4.2. The cyclonic water levels in Table 4.2 include 0.2 m for non-cyclonic water level residual based on analysis of seasonal water levels at Port Hedland over a 20-year period, consistent with Cardno (2011). The adopted non-cyclonic residual is equivalent to the 5% exceedance water level residual over the available data record.

As noted above, wave setup was quantified from the coupled hydrodynamic and wave model and is applicable to a relatively narrow area along the Spoilbank shoreline. As such, wave setup is only applicable to metocean zones that intersect this area and is not adopted for deeper entrance channel and marina basin areas.

Table 4.2: Extreme Water Levels for the Spoilbank Marina (mCD).

ARI (years)	Existing		50-year Planning Period (+0.39m Sea Level Rise)	
	Peak TSWL (excl. wave setup)	Peak TSWL (incl. wave setup)	Peak TSWL (excl. wave setup)	Peak TSWL (incl. wave setup)
1	7.2	7.4	7.6	7.8
5	7.6	7.9	8.0	8.3
20	7.9	8.2	8.3	8.6
100	8.6	9.0	9.0	9.3
500	9.1	9.6	9.5	9.9

4.3.2 Waves

Design wave conditions at the SBM have been defined as the largest wave height result from the subset of modelled events at each recurrence interval, as defined in Section 4.1. Each event was modelled for existing and developed conditions, including both the Base Case and Option 1 concept layouts with both channel options and the Option 2 concept layout that includes the siltation pocket. In this way, the design wave conditions include cases where the marina development increases wave conditions at the northern breakwater head that occur due to wave interaction with the entrance channel. Wave conditions along the internal revetments of the entrance channel and marina basin were defined from simulations of the developed layouts.

Design cyclonic wave conditions for metocean zone 1 (head of the northern entrance structure) are provided in Table 4.3. Design conditions for all metocean zones are provided in Appendix C.

Table 4.3: Design Conditions for Metocean Zone 1.

ARI (years)	Existing Conditions					Sea Level Rise Condition	
	H_s (m)	T_p (s)	Dir (ºTN)	$H_{2\%}$ (m)	H_{max} (m)	H_s (m)	H_{max} (m)
1	1.90	6.0 – 7.5	340 - 0	3.0	3.2	2.20	2.0
5	2.30	6.0 – 8.0	340 - 0	3.6	3.9	2.60	4.4
20	2.70	6.0 – 8.5	340 - 0	4.2	4.6	2.95	5.0
100	3.05	6.0 – 9.5	335 - 350	4.8	5.0	3.20	5.4
500	3.35	6.0 – 10	335 - 350	5.2	5.7	3.55	6.0

Wave heights in shallower water approaching the SBM become limited from available water depth; and seabed slopes (apart from near the dredged channel) are generally mild approaching the Spoil Bank. Observations at the DoT AWAC locations during TC Veronica indicate that Hs/d ratios do not exceed 0.33. By comparison, Hs/d ratios for design conditions summarised in Table 4.3 range between 0.31 to 0.42 and appear consistent with the observations, noting the increased water depth at 100 and 500-year ARI result in higher Hs/d ratios suggesting less energy dissipation when water levels increase.

Estimates of Hmax are also presented adopting a fixed Hmax/Hs ratio of 1.7, as justified in Section 2.5.2. Further, estimates of $H_{2\%}$ are included adopting a fixed $H_{2\%}$/Hs ratio of 1.56 based on the Rayleigh distribution. The assumption that the Rayleigh distribution is valid at the SBM was tested by comparison of available wave height statistics, namely $H_{1/10}$ and $H_{1/3}$, which found the median/mean ratio of $H_{1/10}$:$H_{1/3}$ was 1.27 at the DoT AWAC locations. This aligns with the expected value from the Rayleigh distribution (Goda, 2000) and hence the distribution has been used for the estimate of wave height statistics.

Based on recent shallow water cyclone wave criteria prepared by Baird for another site (confidential) which included 1:30 scale physical modelling of directional cyclonic seas indicates, it was identified that depth limited wave observations with strong shallow water wind growth presented in Babinin *et al* (2001) are applicable. Therefore, Baird recommend that a depth-limited breaking wave height of 0.65 of the water depth, as recommended by Forristall (2004), is appropriate. It is noted that a H/d ratio of 0.65 bounds the dataset of conditions observed at the DoT AWAC locations during TC Veronica. Estimates of Hmax and $H_{2\%}$ included in the summary of design conditions have been checked for depth limitation accordingly.

Design conditions are generated by close tracking extreme cyclonic conditions, and as a result the seastate is a combination of cyclone generated swell and locally generated sea. At the peak of the event both swell and sea contribute similar amounts of energy to the seastate with sea conditions typically larger. Design conditions are therefore presented with a range of peak wave periods, in order to capture the nature of the seastate under peak wave conditions. The lower period relates to the peak period of the sea conditions and the higher period to the swell component.

4.3.3 Sensitivity to Cyclone Track Approach

The variability of the resulting wave conditions at the SBM entrance within the event set for each recurrence interval, as a result of the variability of track alignment, was reviewed. A summary of results from the 100-years ARI event set is presented in Table 4.4 at both an offshore (Beacon 15/16) and inshore (SBM Entrance) location.

Estimates of the 100-year ARI conditions at Beacon 15/16 are available from previous Port Hedland studies (Baird & Associates and Cardno, 2012) that were benchmarked against extreme value analysis of available measured data. The 100-year ARI wave height estimate at Beacon 15/16 is 7.1m (Hs). Wave conditions at Beacon 15/16 from the 100-year ARI event set (in Table 4.4) are generally comparable to the 100-year ARI estimate, however variability exists as a result of storm intensity, proximity to Port Hedland and track approach (noting that all produce a total still water level equal to the 100-year ARI value at the SBM). Where the offshore wave height is lower than the 100-year ARI wave height estimate, it is generally due to a NE track approach and the available fetch over which waves can be generated along those tracks.

The inshore results highlight that the SBM location is more exposed to NNW conditions, with transfer coefficients from N and NNE offshore wave conditions being notably lower. This outcome is driven by the sheltering afforded by the Spoilbank feature and the nearshore bed to the north of the SBM location that refracts wave energy into the Spoilbank shoreline as it propagates from these directions. This outcome is consistent with the MIKE21-BW sensitivity simulations presented in Section 3.9.

Spatial maps of peak significant wave height for the top 5 events from the 100-year ARI event set are presented in Appendix D.

Table 4.4: Summary of Modelled Wave Conditions from the 100-years ARI Event Set. Inshore results are taken from simulations of Existing Conditions.

Event ID	Track Approach	Offshore (Beacon 15/16)			Inshore (SBM Entrance)		
		Hs (m)	Tp (s)	Dir (ºTN)	Hs (m)	Tp (s)	Dir (ºTN)
MC5430	NNW	7.9	9.9	17	2.79	5.5	357
MC10785	NNW	7.2	9	2	2.88	5.8	352
MC19168	NE	6.4	5.6	104	2.91	6.1	346
MC20630	N	7.5	9.9	22	2.56	5.7	359
MC25739	NE	7.1	9	7	2.47	5.8	355
MC32335	NNW	7.3	9.9	312	2.95	6.2	337
MC32805	N	6.2	8.2	25	2.65	6.0	349
MC40562	NNW	7.2	10.8	312	2.66	5.4	334
MC91557	NE	6.9	9	300	2.30	6.3	332
MC92268	NE	6.8	10.8	19	2.14	5.9	345
TC Veronica	NNW	6.4	11.2	7	2.24	9.6	354

4.3.4 Design Wave Heights under Future Shoreline Conditions

The Spoilbank has been assessed to have been in an erosive phase since the mid-1990 and over the time the continual reduction in its plan extent has been observed (see Section 4 and Seashore, 2019). As part of this coastal process assessment for the SBM, the future evolution of the Spoilbank has been estimated, as described in Section 5.3. The resulting future shoreline position and nearshore bathymetry over a 50-year planning horizon (to 2070) has been developed and the impact on design wave conditions assessed.

Five design events, 3 at the 100-years ARI and 1 each at the 20 and 500-years ARI, were modelled with the estimated future Spoilbank condition and an adopted sea level rise of 0.39m consistent with the 2070 forecast horizon. The 100-years ARI condition (Event MC32335) for the estimated future Spoilbank condition in 2070 is presented in Figure 4.3. Presentations for the other events are provided in Appendix D.

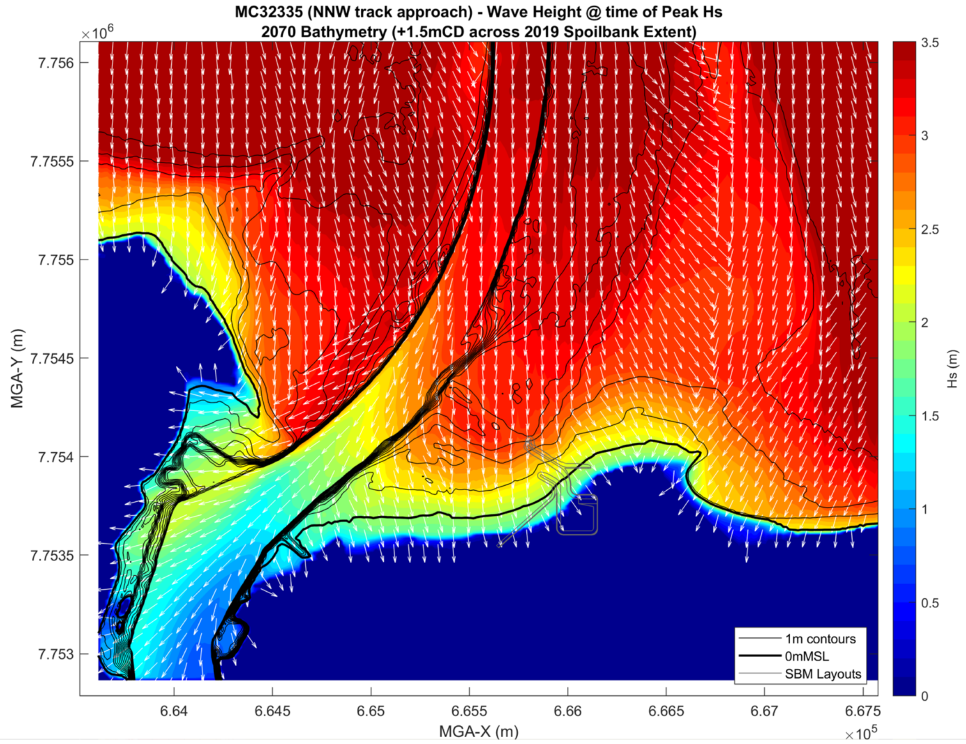


Figure 4.3: Peak wave height from the 100-years ARI event (MC32335) for the estimated future Spoilbank conditions in 2070.

Despite the reduction in sub-aerial landform extent of the Spoilbank, design wave heights do not increase at the breakwater head. For longer return periods, governing conditions tend to arrive from Northerly sectors where the existing Spoilbank extent affords limited protection. Further, it is predicted that bathymetry over the existing extent of the Spoilbank will remain at least 1-1.5m above natural seabed, as has been observed in areas to the north of the Spoilbank and would provide some protection from extreme waves from the North-east sector. Hence, no change to the design wave conditions are required. However, a greater length of the Northern revetment structure is exposed to incoming wave conditions and the design and plan extent of this structure should be reviewed. It is recommended that design wave heights from metocean zone 2 are applied along the full length of the northern revetment.

4.4 Coastal Inundation of Spoilbank (including wave run-up)

An estimate of wave runup on the Western side of the Spoilbank under 100-year AR conditions has been made using the Nielsen and Hanslow (1991) model. The adopted shoreline slope (of 1 in 8) was benchmarked against survey data of the Spoilbank following TC Veronica.

Based on the 100-year ARI cyclonic conditions presented in this report, wave run-up levels ($R_{2\%}$) are estimated at 2.5 m above the peak steady water level (excluding wave setup). The potential elevation of wave run-up is therefore estimated at between 10.9 and 11.9 m CD under present day conditions, and between 11.4 and 12.4 mCD under +0.39m sea level rise scenario (50-year planning period), depending on slope and exposure of Spoilbank location being considered.

The implications of the SBM design have not been considered in this assessment as the reclamation levels and structure elevations were not provided to Baird.

5. Sediment Dynamics

The sediment transport study investigated the following key issues:

- Dynamics of the sand trap and entrance channel;
- Anticipated sedimentation of the approach channel;
- Potential sedimentation of the harbour basin;
- Alongshore sediment transport associated with progressive migration of the Spoilbank.

Sediment dynamics and morphological response of the sand trap, entrance channel, approach channel and marina basin were investigated using the two ambient metocean scenarios, defined in Section 2.6, and an extreme cyclone event.

5.1 Literature Review

A review of available literature and data of relevance to the Spoilbank Marina sediment transport study has focussed on the following topics with the aim of establishing a conceptual sediment transport model that is based on a current understanding of the sediment dynamics in the area:

- Available data for sediment transport studies
- Regional and local geomorphology
- Formation and Historical Evolution of the Spoilbank
- Predictions of Spoilbank Evolution
- Sediment transport along the western shoreline

5.1.1 Available data for sediment transport studies

The following data has been made available for the sediment transport study:

- Metocean data provided by the DoT and PPA, as described in Section 2.
- Bathymetric and topographic surveys provided by DoT and BHP (including years 2008, 2015, 2018, 2019).
- Sediment Samples and Particle Size Distributions (BMT & DoT, 2019)
- Total Suspended Sediment data at the DoT AWAC location (Cardno, 2019)
- Water Quality Report for the Proposed Port Hedland Marina Development (RPS, 2014).

The DoT recently commissioned the collection of a comprehensive set of sediment samples covering the majority of the project site, including along the northern shoreline that incorporates the sand trap feature. Figure 5.1 presents the sediment sample locations. In deeper water areas, along the marina entrance channel, median grain sizes (D50) are in the fine sands range and contain a relatively high percentage of fines (silts and clay) of between 10 to 20%. Along the shoreline areas, sediments are typically a mix of fine and coarse sands with two distinct distributions for each sediment component which contribute roughly 50% each to the total volume.

Two sources of total suspended sediment (TSS) data were provided, that included complimentary descriptions of the TSS concentrations through the water column. Data from the AWAC locations, analysed in Cardno (2019) indicate that TSS is typically between 7 and 10mg/L, with concentrations during high seastate conditions exceeding 11mg/L. Sampling from the Water Quality report (RPS, 2014) indicates those levels are typical of surface concentrations, however seabed concentrations of TSS may exceed 20mg/L during a strong running spring tide during summer.

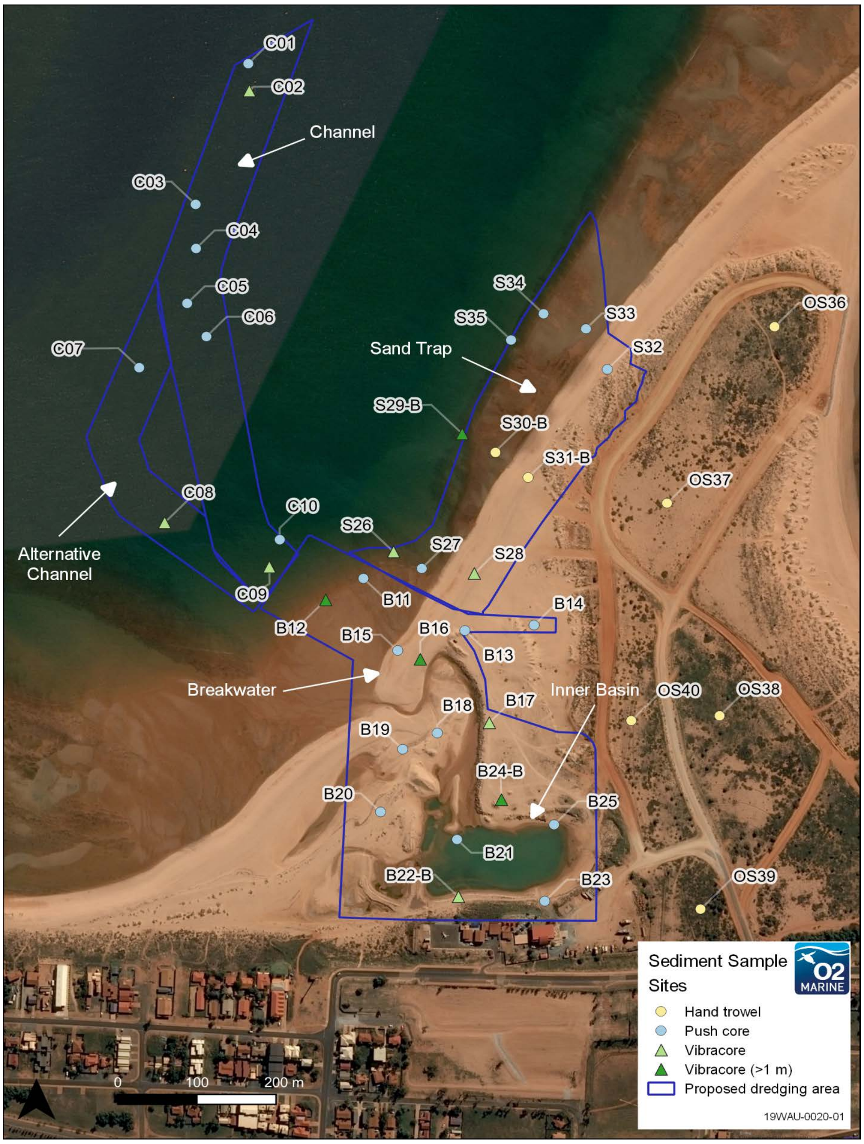


Figure 5.1: Sediment Sampling Locations commissioned by the DoT (from O2 Marine, 2019)

5.1.2 Regional and Local Geomorphology

The general coastal morphology of the Port Hedland area is a limestone barrier system with a shoreline consisting of low coastal cliff and rock formations (Cardno, 2011; GHD, 2015). At the Spoilbank location the underlying bathymetry is characteristic of the macrotidal Pilbara region and is comprised of a mostly flat subtidal area with partly emergent rock features and mobile sediments forming a gently graded intertidal beach (Eliot et al. 2013).

A study of morphodynamics by Seashore (2019), completed for the Spoilbank Marina project, provides a comprehensive summary of the regional and local coastal morphology. Of note for this sediment transport study is that sedimentary features observed on the seabed have structural attributes that suggest a general transition from tidal features offshore towards wave influenced features along the coastline. However, where flow constrictions occur at the coast, ebb shoals and splays occur.

It is important to note that the local geomorphology and sediment transport processes are dominated by human intervention, including the artificially created Spoilbank landform and the creation and maintenance of the Goldsworthy shipping channel.

Historically there has been limited mobile sediments at the shoreline in Port Hedland, however the addition of the sidecast sediments that formed the Spoilbank has provided a source of mobile sediments on the shoreline since the 1960s (Cardno, 2011). Rock structures that underlie much of the Port Hedland coast and its adjacent seabed form a base over which the more mobile sediments (sand and less-mobile gravel) are draped. For the majority of Port Hedland's shoreline, surface and underlying rocks limit the shoreline erosion during storm events. With low ambient wave energy, mobile sediments are spread across a wide area by tropical cyclone conditions, the large tidal range and strong tidal currents which results in low relief seabed features. However, protruding rock features exist that provide either sheltering or redirection of energy from waves or currents, typically enhancing sediment transport along their alignment (Seashore, 2013).

Figure 5.2: presents key geomorphic features offshore of the Spoilbank with main sediment transport pathways inferred. The implication for Spoilbank being that transport is typically shoreward along the sidecast ridge and western shoreline of the Spoilbank.

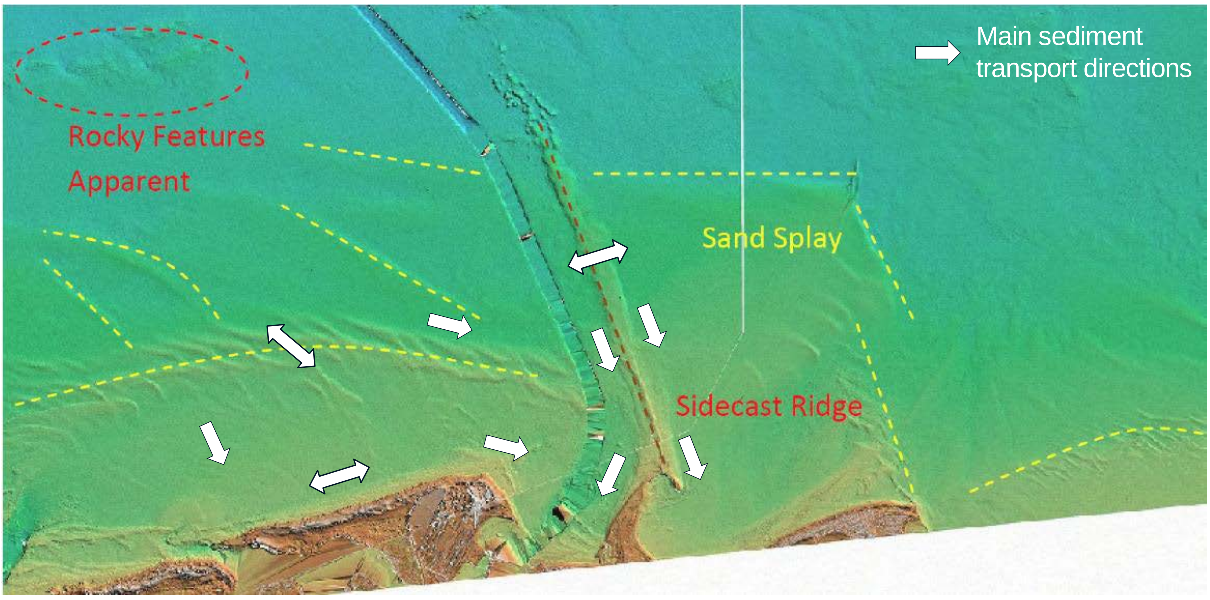


Figure 5.2: Key Coastal Geomorphic Features (reproduced from Seashore, 2013)

5.1.3 Formation and Historical Evolution of the Spoilbank

The present-day Spoilbank is an artificial low sand spit feature parallel to the Goldsworthy channel in Port Hedland. The Spoilbank was formed by the sidecasting from material disposed from dredging the Port Hedland navigational channel between 1965-1970 (Seashore, 2019). The dredged sediment from the capital dredging works included cobbles, gravel and sand and was originally deposited 600 m east of the dredged navigation channel and aligned with the overall eastward littoral drift (Johnson 1963). When completed in 1970 the Spoil Bank formed an island that was located approximately 500 m from the mainland (MRA, 2005). The gap between the mainland and the Spoil Bank was left so minimal interference with the natural littoral drift along the mainland coast would occur (Department of Planning and Urban Development 1992; MRA, 2005). In this way, the Spoilbank was originally intended to be an island that provided wave sheltering for the dredged channel but did not cutoff tidal flows along the shoreline.

However, the Spoilbank had a high rate of evolution, especially between 1969 and 1973 when there was a high occurrence of storm activity. Between 1970 and 1978 it was estimated that transport of the submerged ridge towards the Spoilbank was 847,000 m^3 which accumulated above the +1.0 m CD contour (Rendel Scott Furphy 1980; Seashore, 2019). The mobilised sediments eventually lead to the connection of the island to the shore, which was hastened with the placement of additional spoil from a dredge campaign in 1985 (MRA, 1996). The evolution of the Spoilbank from the sidecast ridge formation in the mid-1960s to 2009 is shown in Figure 5.3. This shows that the western side moved southwards in a smooth structure, under the continued and direct forcing of the predominant north-westerly conditions, while the eastern side moved southwards in a series of spits.

The orientation of the northern end of the Spoilbank which curves to the east suggests that the dominant sediment transport is in an easterly direction (Cardno, 2011). The location of the sand cast ridge is evident in the 2009 panel of Figure 5.3 as a narrow crest of sandy material extending northward from the Spoilbank spit head. This exposed material may be redistributed with the tidal cycle or changing conditions, which is typical of an intertidal bar (Seashore, 2019). From the point at which connection to the shoreline was made in 1985, the Spoilbank continued to 'collapse' with a southward progression of the northern split feature along the alignment of the sidecast ridge and a general rotation of the main trunk of the Spoilbank, most notable in the alignment of the western shoreline.

In the area of the proposed Spoilbank marina, towards the south west corner of the Spoilbank, the existing Port Hedland Yacht Club has been subject to progressive and continual sedimentation. Figure 5.4 presents the coastal form of the area over a 10-year period, which demonstrates the dynamic nature of the shoreline (noting that sand extraction has occurred from time to time) and the formation of an ebb tide shoal, that is also clearly evident in more recent survey data.

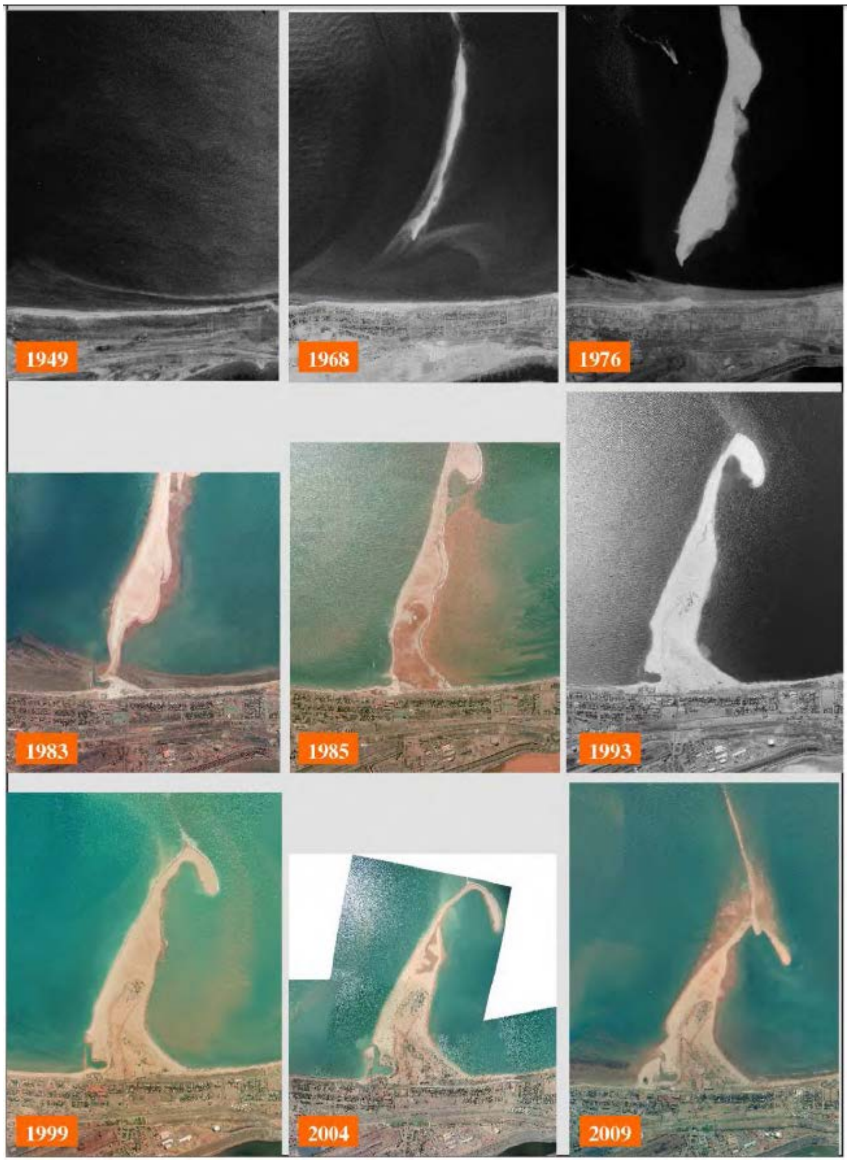


Figure 5.3: Evolution of Port Hedland Spoilbank 1949-2009 (from: Cardno, 2011)

Figure 5.4: Coastal Dynamics West of Port Hedland Yacht Club Basin (from: Cardno, 2011)

5.1.4 Predictions of Spoilbank Evolution

Previous attempts to predict the future form of the Spoilbank have generally followed the logic that the artificial landform will continue to migrate southward, widening and flattening towards the natural shoreline. As there is no longer any dredged sediment being deposited on the Spoilbank, having last been done in 1985 (MRA, 2005), the overall volume and plan extent of the Spoilbank can be expected to reduce over time, based on the observed evolution since that time. Seashore (2019) clearly identifies three phases of observed Spoilbank behaviour; formation/growth (accretion) phase, supply balanced (stable) phase, and a reorientation/rotation (erosion) phase. From that assessment and Baird's analysis of historical shorelines (see Section 5.3 below) the Spoilbank has been in an erosive state since the mid-1990's.

MRA (2005) made estimates of the predicted future shape of the Spoilbank over 20- and 50-year horizons (i.e. out to the years 2025 and 2055), as presented in Figure 5.5. These estimates were based on calculated sediment transport rates, previously observed historical shoreline movements and engineering judgement (MPRA, 2005). Notably, the overall plan extent (sub-aerial area) of the Spoilbank was predicted to be more or less locally retained and redistributed over the first 20 years with a large portion of the sediment volume moving to the south-western and south-eastern corners of the Spoilbank, increasing the western and eastern extent along the shoreline by approximately 1000m and 500m, respectively. Further, the general alignment of the Spoilbank was predicted to remain as it was in 2004, albeit with a reduced northerly extent. While the observed Spoilbank evolution has not followed this predicted form, it is noted that at the time of the MRA (2005) study limited observations of the Spoilbank in its erosive phase were available.

Figure 5.5: Estimated Future Shoreline Positions (MPRA, 2005)

Seashore (2019) reference a previous prediction of Spoilbank behaviour completed in 2013 (Seashore, 2013) and provide a comparison of the prediction to the observed change since that time. Initial predictions were based on migration rates between 2000 and 2009, noting that the Spoilbank had entered an eroding phase, where supply from the submerged sidecast ridge is lower than the rate of landward material movement (Seashore, 2019). The prediction, reproduced in Figure 5.6, reasonably estimated the southward movement of the northern extent and the clockwise rotation of the western shoreline, however overpredicted the accretion of the south-east and south-west shorelines. Overall, Seashore (2019) estimates that predictions were out by a factor of 4x, although this may be impacted by the use of aerial imagery without accounting for the macro-tidal water level variation in 'observed' shoreline position.

Figure 5.6: Predicted and observed behaviour of the Spoilbank (Seastate, 2019)

As a basis for comparison, Figure 5.7 presents the +1mAHD shoreline position (see Section 5.3 for method of determination) in 2004, 2009 and 2019 (the2004 and 2009 shorelines having been used as a basis for predictions in MRA, 2005 and Seashore, 2013, respectively). In summary, previous predictions of future shoreline evolution have:

- Underestimated the observed clockwise rotation of the western shoreline;
- Overestimated the flattening and widening of the Spoilbank, and associated accretion of the shorelines in the south-west and south-east corners;
- Overestimated the retained volume (plan area) of the Spoilbank.

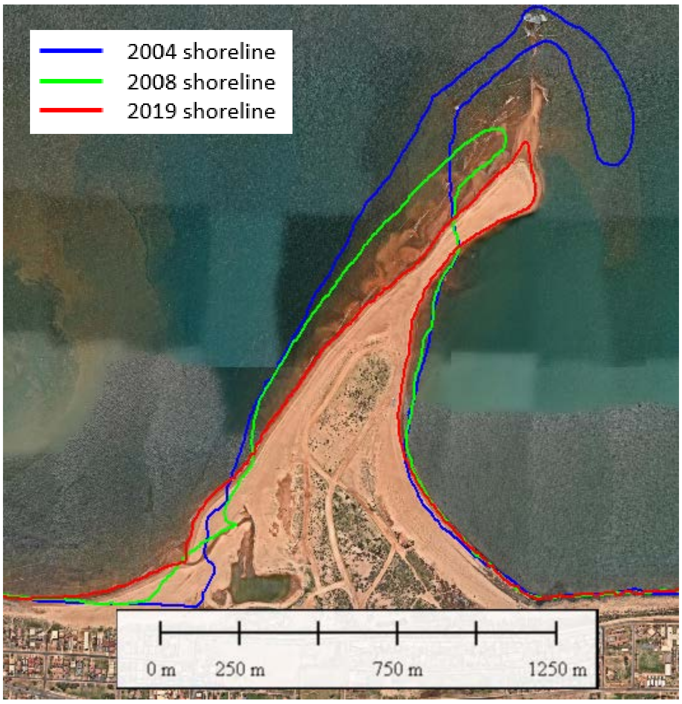


Figure 5.7: Observed +1mAHD shoreline positions in 2004, 2009 and 2019 (derived from CoastSat)

5.1.5 Sediment Transport along the Western Shoreline

Numerous estimates of alongshore transport rates have been made along the western shoreline of the Spoilbank. The range of estimates are summarised below, and although the annual rates vary, the driver for alongshore sediment transport is consistently deemed to be driven by north to north-westerly wave conditions under ambient conditions but dominated by episodic extreme waves and elevated water levels as a result of tropical cyclones. The following alongshore transport rates have been made in the past:

- Rendel Scott Furphy (1980) estimated that the rate of southerly sediment transport along the Spoilbank between 1970 and 1978 was around 14,000 m^3/yr, with the vast majority of this transport occurring on the western side of the Spoilbank.
- Department of Planning and Urban Development (1992) estimated an alongshore transport along the western side of the Spoilbank of 13,000 m^3/yr.
- MAK JaP (2005) estimated the southerly transport of sediment along the Spoilbank as being 50,000 m^3/yr. This estimate was obtained via MRA (2005), and no details as to the proportion of transport along the western shoreline could be found.
- MRA (2005) estimated that there was a net southerly transport of approximately 35,000 m^3/yr on the western side of the Spoil Bank for the 1984 to 1999 period, by comparison of surveys taken in those years.

- Cardno Lawson Treloar (2012) estimated that under ambient conditions, with consideration of summer and winter seasonal conditions, between 6,000 and 8000 m^3/yr of southerly transport occurs on the western shoreline.
- Seashore (2019) estimated a background transport rate of 19,000m^3/yr plus 40,000m^3 per storm when only tropical cyclones causing extreme waves at Port Hedland are considered.

Based on the above references, alongshore sediment transport rates could be summarised as follows:

- 6,000 to 19,000m^3/yr under ambient conditions
- 30,000 to 40,000m^3 per cyclone event (on average)

These summary estimates of alongshore transport are based on the currently available literature, typically derived from comparison of survey data or other mapping techniques, and to date no process-based assessment of transport rates has been identified. The estimates have been updated with a process-based analysis completed as part of this assessment, as presented in Section 5.4.

5.1.6 Siltation at Port Hedland

Siltation of fines are noted to be highly variable at Port Hedland, ranging from 0.1 to 0.6m/yr based on an analysis by Paul and Lustig (1975). MRA (2005) made an assessment of accumulated fine sediment in the Nelson Point Tug Harbour, adopting a value of 0.05m/yr of siltation. This value, however, is influenced by the fact that the Tug Harbour is a heavily trafficked area where tug prop wash would act to resuspend the settled fines. Baird (2012) completed an analysis of available surveys at the Nelson Point Tug Harbour, the TCLOF area (near Hunt Point) and in Stingray creek and determined a siltation estimate of up to 0.25m/yr.

From available suspended sediment data, derived from AWAC backscatter signals by Cardno (2019), there is a good description of the background and episodic fluctuations of suspended sediment concentrations in the water column in close proximity to the proposed Spoilbank location. From the data, a typical range of between 7 and 10mg/L is observed, with concentrations during TC Veronica reaching 11.5mg/L.

5.2 Conceptual Sediment Transport Model

Following a review of available literature and data, a relatively robust conceptual model of sediment transport along the western shoreline of the Spoilbank can be developed. To further inform a conceptual sediment transport model, a difference plot of surveys from pre- and post- TC Veronica was utilised, as presented Figure 5.8. Key processes include:

1. Inundation and Over wash of the Northern Spit
2. Inundation and Over wash of the Northern shoreline
3. Wave-driven Southerly Longshore Transport
4. Sedimentation of the dredged Entrance Channel
5. Formation of an ebb tide shoal through exchange from the dredged basin
6. Westerly longshore transport towards (and possibly into) the Goldsworthy channel

With the dominant southerly drivers for sediment transport and absence of a sediment source to replenish Spoilbank, the mechanisms for continued rotation of the westerly shoreline and loss of overall volume (and plan area) of the Spoilbank is clear.

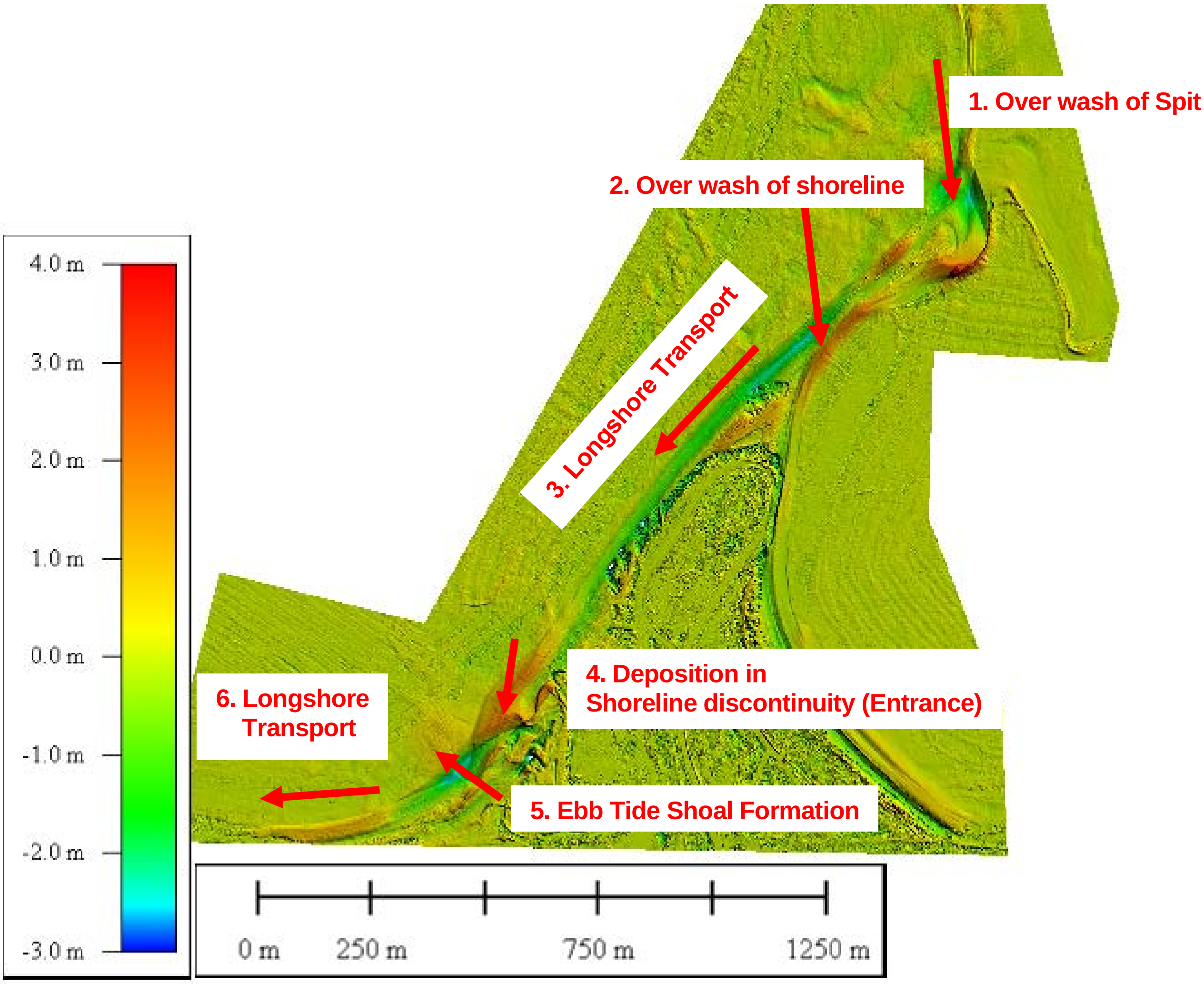


Figure 5.8: Conceptual Sediment Transport along the Western Shoreline of Spoilbank, presented over a difference plot between pre- and post- TC Veronica surveys

For the purposes of benchmarking the sediment transport analyses the volume changes calculated from pre- and post- TC Veronica surveys can be used to infer transport rates resulting from that event. Figure 5.9 provides a schematic of the inferred transport rates as a result of TC Veronica. The transport rates, as they relate the western shoreline, can be summarised as follows:

- Over wash of the northern spit are in the order of 20,000m^3, with a ~10% of this volume lost from the system.
- Erosion of the western shoreline in the order 50,000m^3, made up of 20,000m^3 in over wash of the northern shoreline and 30,000m^3 in south-westerly alongshore transport. Approximately 20% of this volume lost from the system.
- Ebb tide shoal formation and westerly alongshore transport in the order of 15,000m^3, with a 10% loss of this volume from the system

Overall, it is estimated that around 22,500m^3 of sediment was lost from the Spoilbank area, with around 60% of the loss occurring from the western side through over wash and longshore transport.

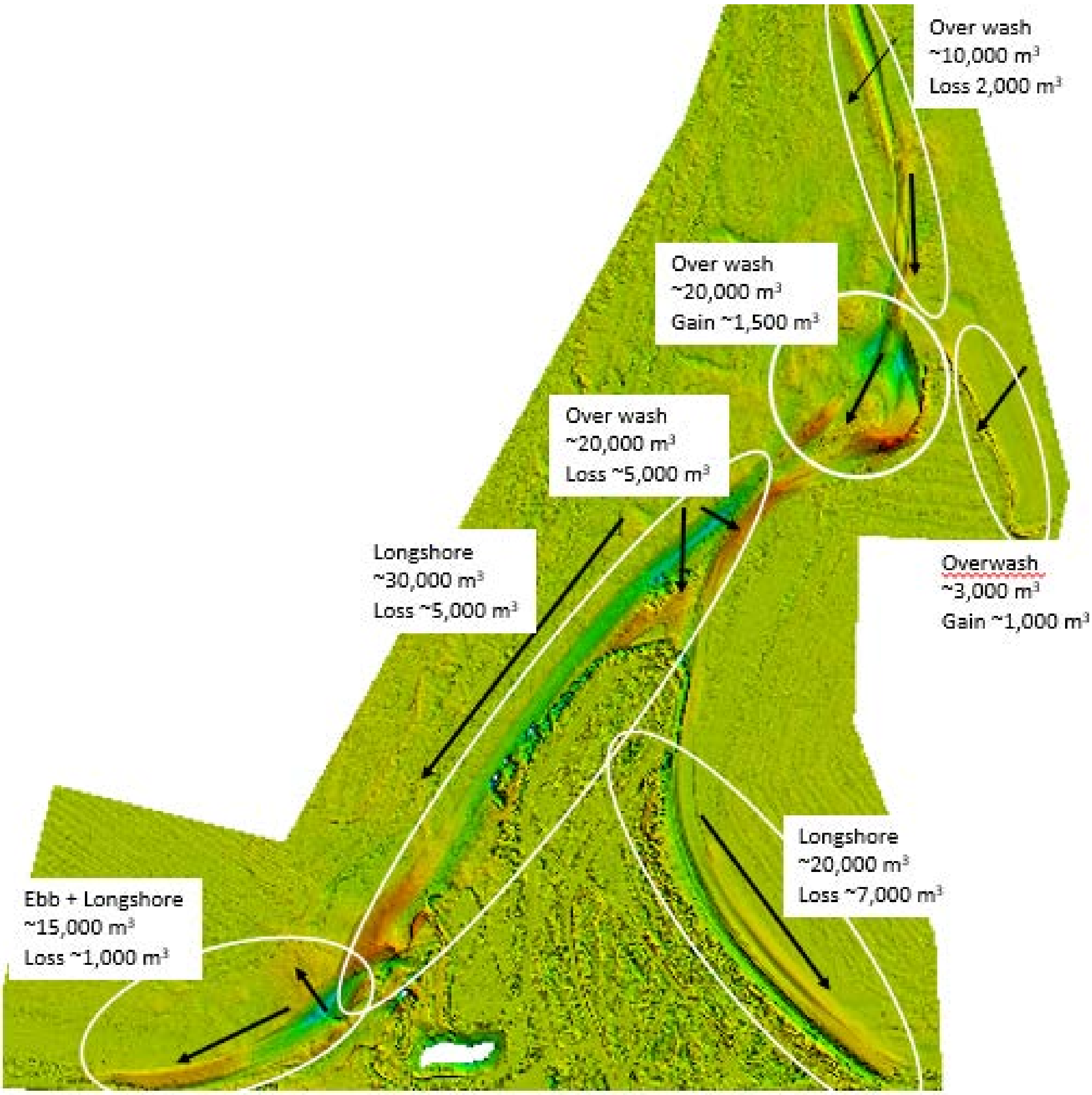


Figure 5.9: Schematic of Sediment Transport volumes under TC Veronica based on comparison of the Aug 2018 and May 2019 surveys.

5.3 Future Spoilbank Evolution

To inform a prediction of future Spoilbank evolution, two-methods were applied; namely, analysis and extrapolation of historical shoreline positions and a processes-based quantification of sediment transport pathways along the western shoreline.

To derive a robust analysis of historical shoreline behaviour a dataset of high temporal resolution is required. Such a dataset was developed using the CoastSat toolbox (Vos et. al., 2019). CoastSat is an open-source software toolkit that enables time-series of shoreline position to be obtained at any sandy coastline from approximately 30 years of publicly available satellite imagery. The toolkit exploits the capabilities of Google Earth Engine to efficiently retrieve Landsat and Sentinel-2 images. The resulting images are pre-processed to remove the influence of clouds and enhance spatial resolution, before applying a shoreline detection algorithm. This shoreline detection technique combines a supervised image classification and a sub-pixel resolution border segmentation to map the position of the shoreline. Positional accuracy of the shoreline mapping is dependent on image quality (e.g. resolution and interference from clouds etc.), however has been shown to produce a positional accuracy of less than 10m and as good as 2m (Vos et. al., 2019).

Imagery was extracted from the following satellite missions:

- 719 *Landsat 5* satellite images were downloaded and analysed
- 267 *Landsat 8* satellite images were downloaded and analysed
- 157 *Sentinel-2* satellite images were downloaded and analysed

Given the macrotidal environment the observed shoreline position can be highly dependent on the level of the tide. To account for this, each satellite image was correlated with Port Hedland predicted tides, using the embedded date and time stamp of the image. This allowed each image and mapped shoreline to be grouped into tide level ranges. Figure 5.10 presents the available mapped shorelines for two tide ranges; 0 to +0.5 mMSL and +1.5 to +2.0 mMSL. With over 100 shorelines mapped between 1986 and 2019 at each tide level, a robust analysis of shoreline change can be made.

Shoreline positions for all available satellite images were extracted along 4 profiles (see Figure 5.10), and plotted against time, as presented in Figure 5.11. The timeseries of the shoreline positions demonstrate the three phases of Spoilbank evolution, as defined in Seashore (2019), with a stable shoreline position being achieved at the two northern transects in the mid-1990s and a clear erosional trend across all transects starting around 2003. Considering data from post-2003, an extrapolation of shoreline position can be made out to defined forecast horizons. This was done for the years 2030, 2040 and 2070, as presented in Figure 5.12. Using these extrapolated shoreline positions, an estimate of the western shoreline position could be made. In deriving these future predicted shorelines, the following observations were taken into consideration:

- The southward progress of the northern spit feature appears to follow a relatively straight track aligned with the sidecast ridge.
- There is negligible change to the native shoreline positions to the east and west of the Spoilbank, that is, no accretional trend was identified. This suggests that sediment is being efficiently transported along these shorelines and away from the Spoilbank “sediment cell”
- There is observed, albeit modest, accretion of the south west and south east corners of the Spoilbank. The south west area appears to reach capacity when it becomes aligned with the western shoreline to the north and bypassing of this area may then start to occur.

Based on the above, the future estimated shoreline positions are presented in Figure 5.13. It is noted that the position of the SBM concept is shown for reference only, and the calculation of the future shoreline position has not considered structures in place in the shoreline.

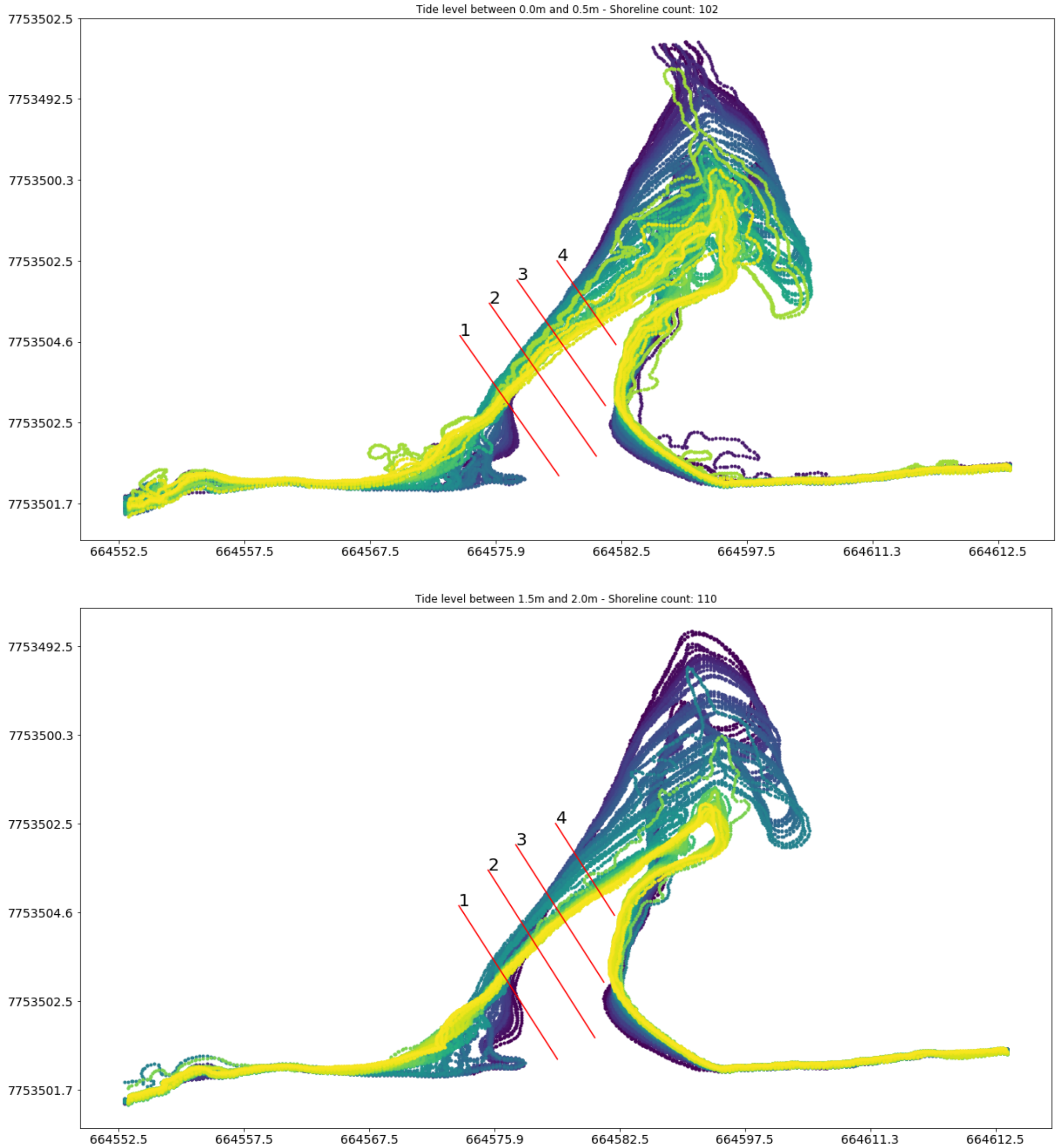


Figure 5.10: Mapped shorelines from the CoastSat Toolbox for tide ranges 0 to +0.5mMSL (top) and +1.5 to +2.0mMSL (bottom). Shoreline dates range from 1986 (dark blue) to 2019 (yellow).

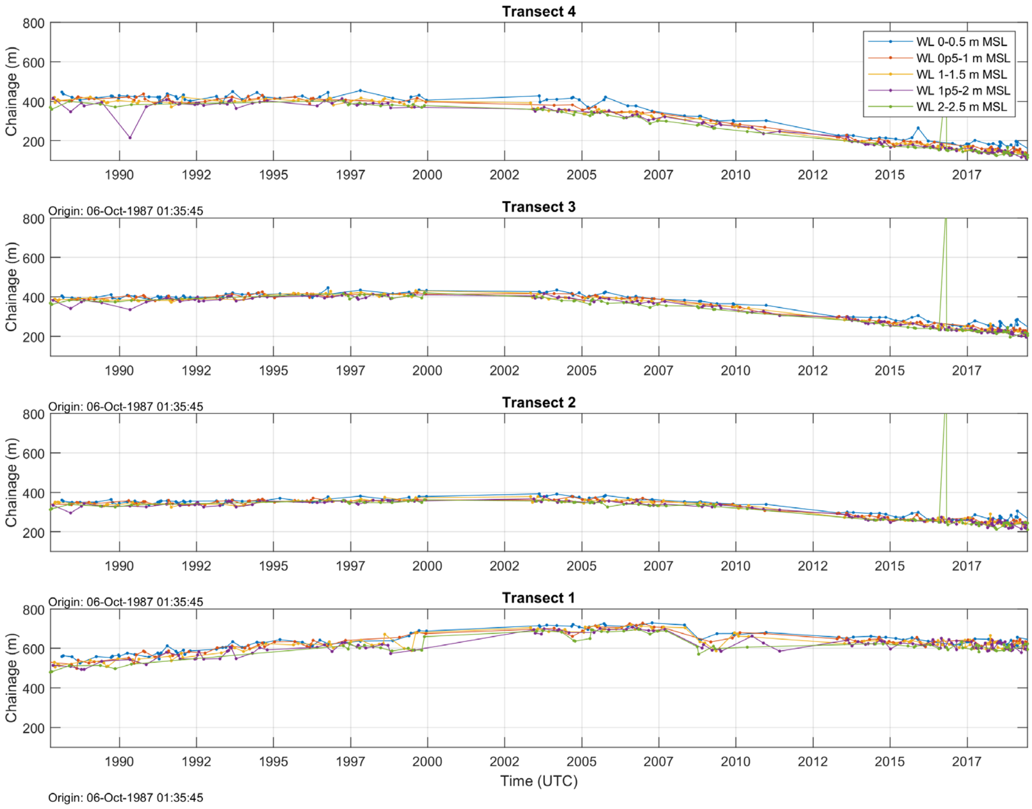


Figure 5.11: Timeseries of shoreline position for five tide ranges at the four transects identified in Figure 5.10

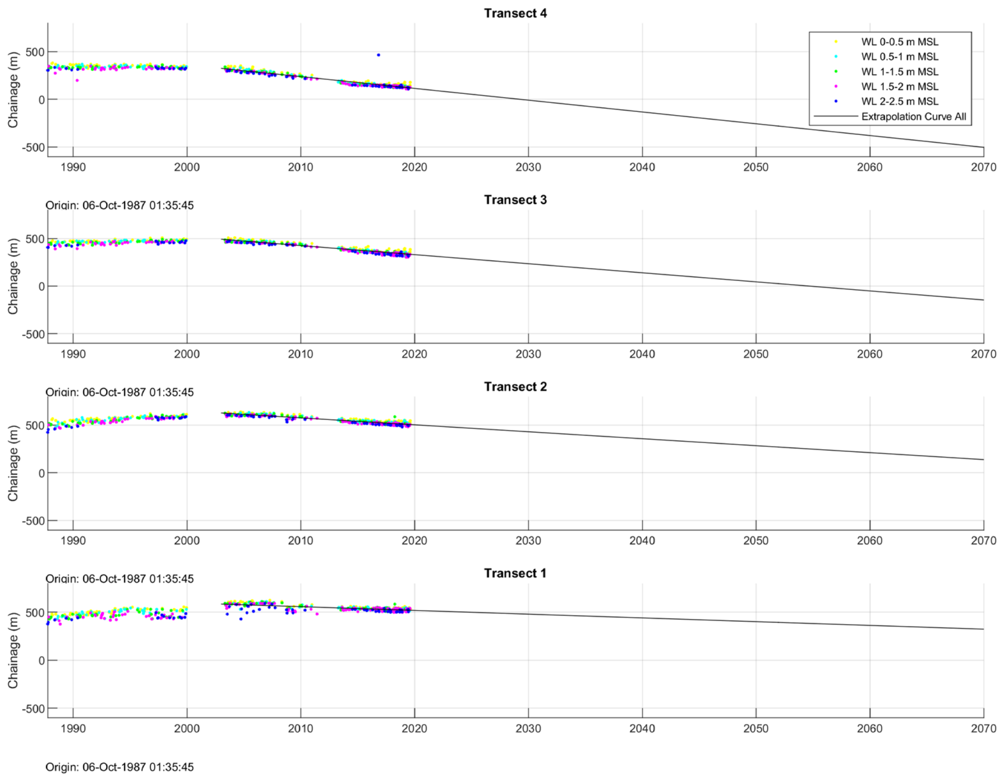


Figure 5.12: Extrapolation of shoreline position timeseries using post 2003 satellite derived shoreline positions

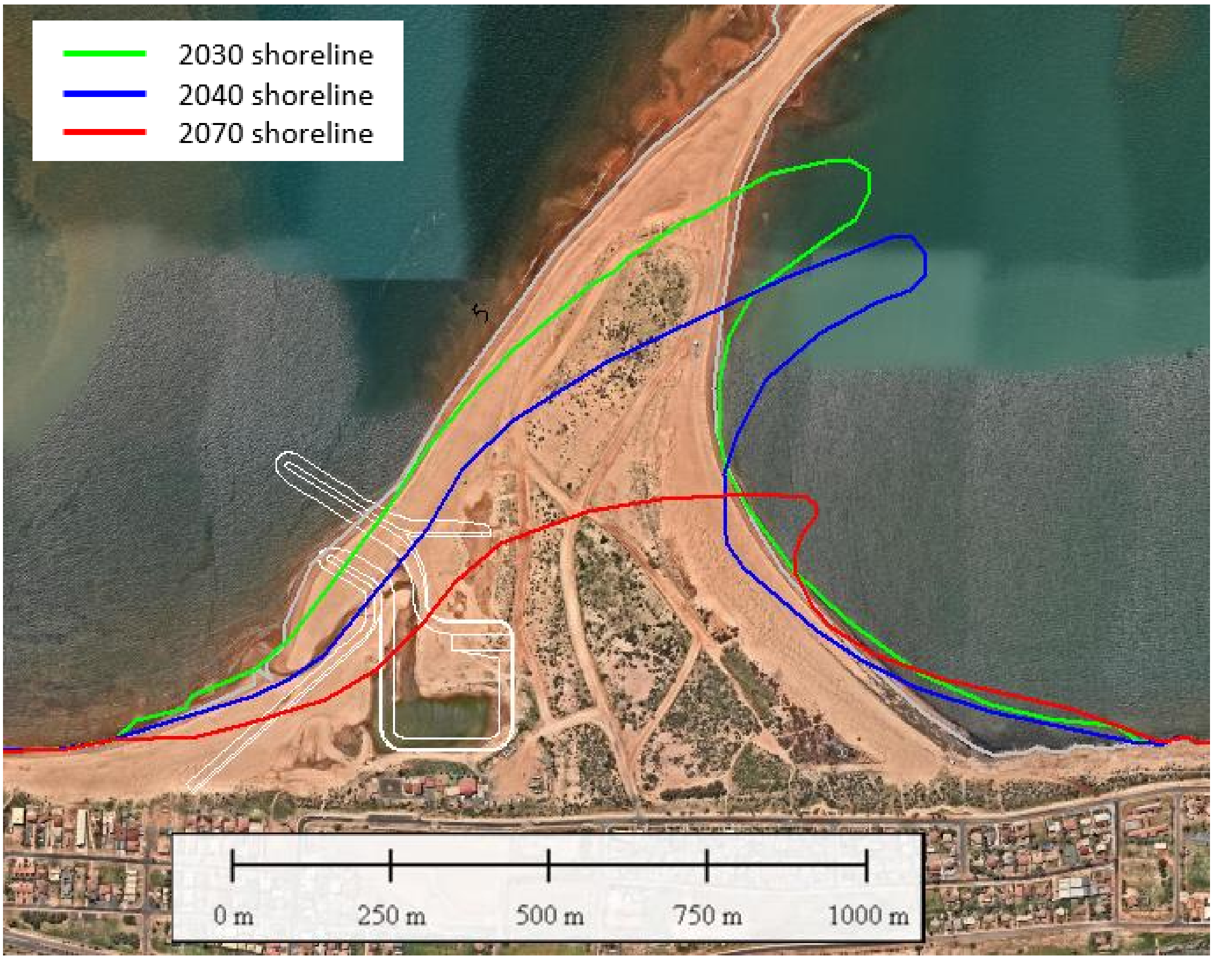


Figure 5.13: Estimated future shoreline positions over a 10, 20 and 50-years horizon. The Marina concept is shown for reference only.

For the purposes of modelling coastal processes on the western spoilbank for future horizons, the future shoreline position is required, but also a description of the offshore bathymetry over areas currently occupied by the Spoilbank. MRA (2005) notes that the dredge spoil used to create the Spoilbank was a variable mixture of rock cobbles, sand and fines. As the Spoilbank has migrated, a rocky base at about 1 to 1.5 m above the natural surface level has been retained. It was assumed that the ratio of sand to rock is relatively constant throughout the dredge spoil so this amount of rock would remain in most areas after the sand has been transported (MRA, 2005). This assumption has been adopted and correlates well with profiles extracted from recent bathymetric survey data collected in 2008, 2018 and 2019. In fact, the nearshore profile can be readily idealised by a fitting a linear slope between the +1mCD and +4mCD contours, see Figure 5.14, with the +1mCD contour having not changed appreciably since 2008.

Based on the assumption a remnant rocky base at 1m to 1.5m above the natural seabed will remain as the shoreline recedes, the spatial extent of the offshore bathymetry in the 10yr, 20yr and 50yr future evolution scenarios of the Spoilbank (Figure 5.14) has then been estimated using a GIS based approach. This was used as a basis for assessing wave conditions affecting the marina structures in future planning periods, with the sediment transport model used to investigate sediment transport rates along the western shoreline of the Spoilbank for the present day and the future Spoilbank shoreline alignments (2030, 2040 and 2070).

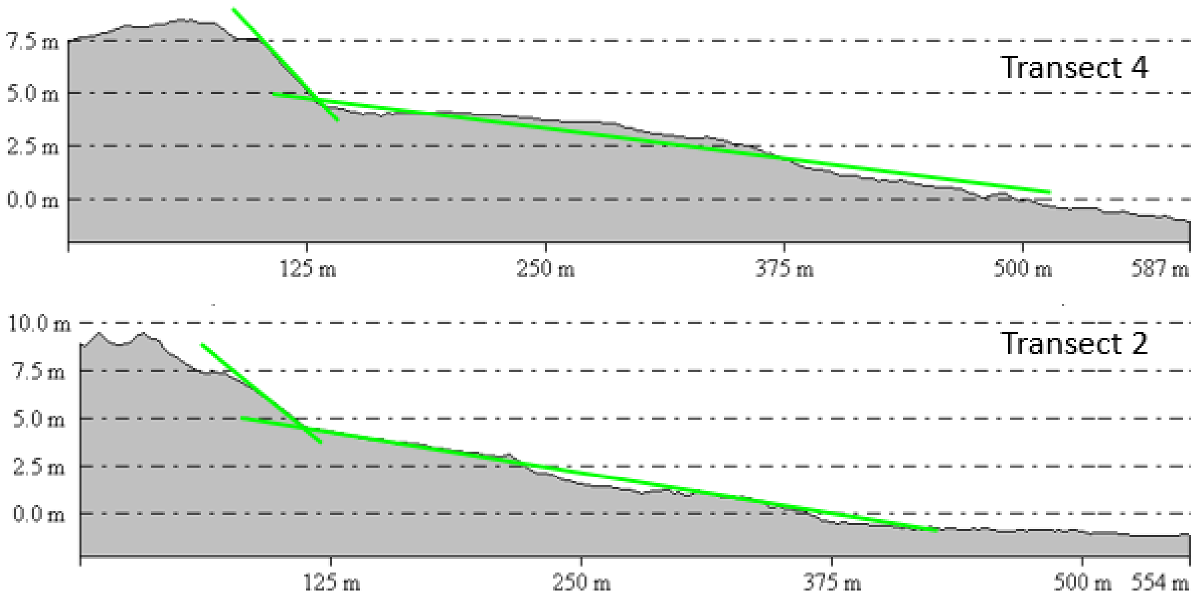


Figure 5.14: Bathymetric profiles extracted along Transects 2 and 4 (see Figure 5.7) from the May 2019 survey

5.4 Longshore Transport Estimates

As noted in the conceptual sediment transport model (see Figure 5.8) and volumetric analysis of the Spoilbank change during TC Veronica (see Figure 5.9), much of the Spoilbank evolution is driven by longshore transport in a southward direction along the western shoreline. This has direct implications for the SBM entrance and maintenance of a navigable entrance channel. Existing literature and analysis of Spoilbank evolution (see Section5.1.5) indicates that longshore transport along the western shoreline is dominated by episodic cyclonic conditions. An analysis of potential longshore transport rates has therefore been completed in this study.

Recent sediment sampling in the vicinity of the SBM location indicated that the seabed sediment is variable in composition with fine sands (of relatively high fines content) and coarse sands being notable near the shoreline areas. Observations of Spoilbank evolution suggest that the majority of the alongshore transport occurs above the +0mMSL (+4mCD) contour along the western shoreline. A number of sediment samples were taken in this longshore transport zone, and while variable in composition are typically made up of:

- Gravels >2mm in size (15-30%);
- Coarse sand with a D50 of ~1mm (30-45%);
- Fine sand with a D50 of ~0.2mm (40-45%), with a fines content of 5-10%.

An example of such a distribution can be seen in the PSD data from sample location S30-B (see Figure 5.1 for location), presented in Figure 5.15.

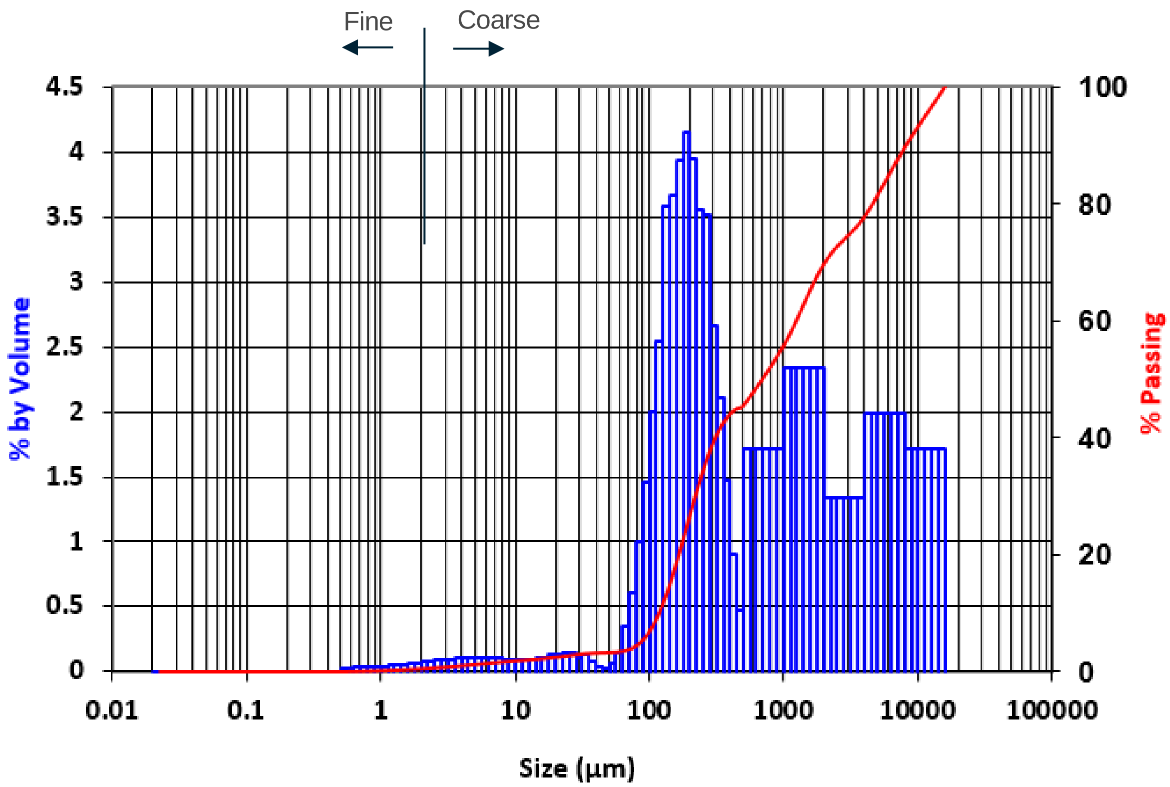


Figure 5.15: Particle Size Distribution Curves from location S31 (Refer Figure 5.1) showing two distinct sediment distributions.

Such a distribution is challenging for process-based modelling. To account for the composite sediment distribution, sediment transport processes were modelled as two distinct sediment fractions, coarse sand and fine sand, and the results combined adopting an in-situ composition of 55% fine sand and 45% coarse sand. Gravels were excluded from the modelling as the resulting potential transport rates are considered low.

Potential longshore transport rates have been modelled using the DHI Litpack modelling system (*Litdrift* module). The Litdrift module is a cross-shore profile based numerical model that provides a deterministic description the littoral drift. It has been widely used to simulate the longshore transport potential of beach profiles under ambient and storm conditions. Litdrift simulates the cross-shore distribution of the wave height, setup and longshore current at a single profile, providing a detailed description of the longshore sediment transport distribution based on the profile bathymetry (DHI, 2019). The model accounts for irregular waves, water levels, tidal currents, wind stresses, bottom friction, wave refraction and shoaling, wave breaking and non-uniform sediment distributions.

The potential longshore transport rates have been calculated at two cross-shore profiles along the western shoreline, as shown in Figure 5.16.

Figure 5.16: Cross -shore profile locations for longshore sediment transport modelling under present day Spoilbank condition

The sediment specification for the longshore transport modelling was consistent with the description above, with distinct sediment fractions for fine and coarse sand modelling. For fine sands, a spatial sediment grain size (D_{50}) between 0.1 mm (offshore profile extent) and 0.2 mm (at the shoreline) was adopted with linear interpolation along the profile applied. A graded gran size distribution, with grading factor of 2.5, was used based on the available PSD information. For coarse sands, a constant D_{50} of 1mm was applied.

Metocean inputs to the Litdrift model included water level, currents and wave conditions appropriate for each profile that was directly obtained from Delft3D simulations of the scenario being considered.

Recent observations (from survey comparisons) provide the clearest picture yet as to the evolution of the Spoilbank in response to a large cyclone event. As defined in Figure 5.9, longshore transport of approximately 30,000m^3 occurred along the western shoreline during TC Veronica which along with an allowance for lost volume for the system provides a suitable estimate to benchmark the longshore transport model of around 35,000m^3. The modelled metocean conditions for TC Veronica (see Delft3D model calibration in Section 3.6.2) was applied to each Litdrift profile.

The results, summarised in Table 5.1, indicate longshore transport estimates of between 31,600 m^3 and 39,500 m^3 during the event, which aligns well with the benchmark value described above. The difference in transport estimates between profiles is due to the difference in cross shore alignment to the incoming metocean conditions.

With the model setup and assumptions suitably validated, modelled design conditions for the 20, 100 and 500-years ARI conditions were applied. Conditions for the 1 and 5-years ARI events were also considered, by scaling the metocean inputs for the modelled 20-years ARI case to match design conditions for the lower return period events.

Ambient seasonal conditions were modelled for two 1-month simulations, using timeseries of modelled hindcasts of water levels, currents and waves. The results from each 1-month seasonal period were multiplied by 6.5 to scale each season to 26-weeks.

In order to derive an estimate of the average annual longshore transport potential, a weighted average of the cyclonic and ambient results was calculated based on the encounter probability of each event during a 1-year period. Ambient conditions were assigned an encounter probability of 100%, given they are considered representative of typical seasonal conditions that occur year on year. Based on this method, the average annual longshore transport rate is estimated as being between 38,400 (Profile 1) and 49,800 m^3/year (Profile 2) towards the south. A summary of the results for all scenarios is provided in Table 5.1. The results are presented as net littoral drift, and transport to the south is a positive (+ve) value.

Table 5.1: Summary of longshore transport potential on the Western Shoreline of the Spoilbank

Scenario	Net Transport (m^3 South)	Encounter Probability	Average Annual Net Transport (m^3/yr South)
Profile 1			
TC Veronica	31,600	N/A	-
Ambient (Wet Season)	6,800*	1.0	38,400
Ambient (Dry Season)	8,500*	1.0	
1-yr ARI	19,100	0.63	
5-yr ARI	36,500	0.18	
20-yr ARI	63,300	0.049	
100-yr ARI	100,200	0.01	
500-yr ARI	138,200	0.002	
Profile 2			
TC Veronica	39,500	N/A	-
Ambient (Wet Season)	7,300*	1.0	49,800
Ambient (Dry Season)	10,100*	1.0	
1-yr ARI	27,200	0.63	
5-yr ARI	49,600	0.18	
20-yr ARI	83,300	0.049	
100-yr ARI	119,400	0.01	
500-yr ARI	158,300	0.002	

* Seasonal estimates are 6-month equivalent values of net transport volumes.

It is noted that despite TC Veronica being considered a 20+ years ARI event (approx.) in terms of water levels and waves, the longshore transport for the event is equivalent to the 5-year ARI design event. The longshore transport result in Table 5.1 for TC Veronica used measured wave conditions from the DoT (HD02) AWAC location as input for the Litprof simulation. Wave conditions for each design scenario (i.e.

ARI cases) were taken from numerical simulations of the design event set using a wave model that is biased high against wave measurements during TC Veronica. This was accepted as being suitably conservative for design wave criteria and will result in longshore transport volumes being slightly conservative.

The distribution of longshore transport during TC Veronica is presented in Figure 5.17, which indicates that the vast majority of longshore transport occurs above mean sea level (0mMSL contour level). This is consistent across all Litdrift cyclonic scenarios and is in keeping with observed changes along the western shoreline during TC Veronica.

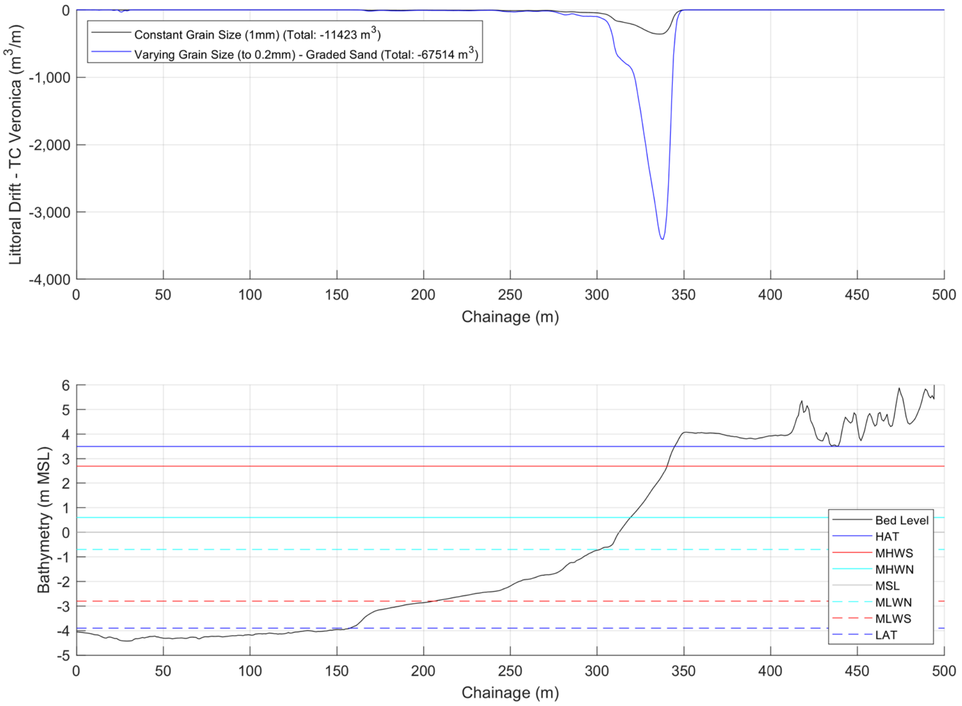


Figure 5.17: Modelled longshore transport for Profile 2 during TC Veronica for both the coarse sand and fine sand fractions. The transport potential from each fraction is averaged based on a 50/50 in-situ seabed composition.

An interpretation of the Litdrift modelling outcomes, presented in Table 5.1, is summarised as follows:

- Potential transport volumes are dominated by cyclonic conditions, with ambient rates during both winter and summer less than the 1-year ARI cyclone event.
- There is little variation in the transport potential between seasons. The reason for this is due to the fact that ambient conditions are dominated by the tides, such that seasonal variation in water levels and currents is marginal with respect to sediment transport potential. Further, the modelling suggests that the ambient wave climate at the shoreline is typically below the threshold for significant longshore transport to occur. As such, the seasonal variation in winds and waves is not influential to the ambient longshore transport potential.
- Longshore transport potential during cyclonic conditions predominantly occurs at water levels above 0mMSL. This is principaly a result of the fact that elevated water levels permit increased wave conditions at the shoreline, but at the same time reduce the transport potential further along the profile due to increased water depth.
- Longshore transport under ambient conditions is tidally dependant, occuring close to the shoreline at high water and but further along the profile (deeper sections) during low water. This may have implications for maintanence of the entrance chanel depths.

- A potential transport gradient between Profile 1 (north) and Profile 2 (south) exists due to the difference in alignment of the shorelines, which would suggest an overall erosionary trend along the western shoreline.
- While average potential transport rates are 38,400 m^3/year (Profile 1) and 49,800 m^3/year (Profile 2) towards the south, less than half of the totals are driven by ambient conditions. As such the annual longshore transport rates will be variable year on year and have a likely range of 20,000 m^3/year to 100,000 m^3/year depending on the severity and frequency of cyclone events.

5.5 Delft3D Online Sediment Modelling

Sediment transport modelling has been completed using the Delft3D Online Sediment model system with coupled hydrodynamic and wave forcing. The wave and hydrodynamic model setup and calibration is described in Section 3.6. It is noted that Delft3D Online Sediment is limited in its ability to resolve longshore and cross-shore sediment transport, however was applied to the study to quantify the sedimentation potential in the outer channel, siltation of the marina basin and the bypass potential of the SBM entrance structure options.

A key addition to the model setup is the use of the wave surface roller model in Delft3D, which has been demonstrated to provide an improved description of surf zone currents (Luijendijk et. al., 2017), critical for the description of sediment transport processes in the vicinity of the SBM. The Roller model incorporates the effect of breaker delay due to the presence of the surface roller, which is a phenomenon that occurs when waves break in the nearshore. The presence of the roller results in a non-zero fraction of broken waves farther into the surf zone than without the roller which acts to enhance onshore sediment transport and shifts the peak of the cross-shore distribution of the longshore current. The factor for erosion of dry adjacent dry cells was also set to 1, which acts to better replicate the shoreline response at the water line by distributing the erosion experienced at the last active grid cell at the shoreline to the adjacent dry cells in the model.

5.5.1 Sediment Transport Formulations

For the sand fractions, the TRANMOR 2004 sediment transport formulation, which is available in Delft3D and is suitable for non-cohesive sediments, has been applied. This sand transport formulation is documented in van Rijn (2007). The TR2004 model is significantly more accurate and robust compared to earlier sediment transport models. The key changes in the TR2004 model, compared to earlier transport models such as the van Rijn (1993) model, are associated with:

- Bed roughness prediction;
- Influence of Bed forms, via an effective roughness model;
- Wave-induced transport; and
- Reference sediment concentration above the seabed.

Delft3D with the TRANMOR 2004 sediment transport formulation has been used in a number of entrance and channel morphology studies over the last ten years including well validated models that have been developed for dynamic entrances with wave-current interactions. Two such studies of note, with publicly available reports, include the Brisbane Water (NSW) estuary processes study and the Lake Illawarra Entrance Study. At Lake Illawarra, revalidation of the Deflt3D entrance morphological model using the TR2004 sediment transport model demonstrated substantially improved agreement between modelled and measured entrance morphological changes (Taylor et al, 2008). The model system was also applied in the coastal processes investigations for the Port Hedland Outer Harbour project and by Baird recently for the Onslow Marine Supply Base (OMSB) development at Beadon Creek, Onslow.

In this study, bed roughness due to bed forms was included in the sediment transport and hydrodynamic model processes based on the model of van Rijn (2004).

Fine sediments were modelled in the same Delft3D model as the sand fraction but using the Partheniades-Krone formulations (Partheniades, 1965) for cohesive sediment. This model calculates the sediment fluxes between the water phase and the bed. The Partheniades-Krone formulations require the specification of the critical shear stresses for erosion and sedimentation, the maximum erosion rate and a hindered settling velocity.

The sediment transport model has been setup to model two sand fractions (D50 = 150 µm, 1000 µm) and one fine sediment fraction specified with a fall velocity of 0.5 mm/s based on available PSD and sediment sample data. Sediment availability was established in the model as three mixed sediment layers with the aim of replicating the variability in the sediment composition across the Spoilbank area. There were broadly defined based on elevation ranges as follows:

- Above +3mMSL: Fine to coarse sands with low fines content (5%), representative of sediment samples taken on the subaerial areas of the Spoilbank.
- Between +2 to 3mMSL: Coarse sands with some fine sand (20%), representative of the apparent underlying coarse sediment layer that is observed in areas north of the Spoilbank and along the shore face of the Spoilbank.
- Below +2mMSL: Fine to coarse sands with high fines content (20%), representative of the seabed composition in the nearshore ad intertidal areas. A sediment thickness layer of 2m (below the surveyed seabed levels) was defined that aligns with the approximated underlying competent bed layer defined in Golders (2009 and Shorewater Marine, 2016).

The initial distribution map of the seabed surface layer is presented in Figure 5.18, which also includes areas with no mobile sediments (i.e. rocky / consolidated areas) based on review of the available seabed data and survey (bed change) comparisons.

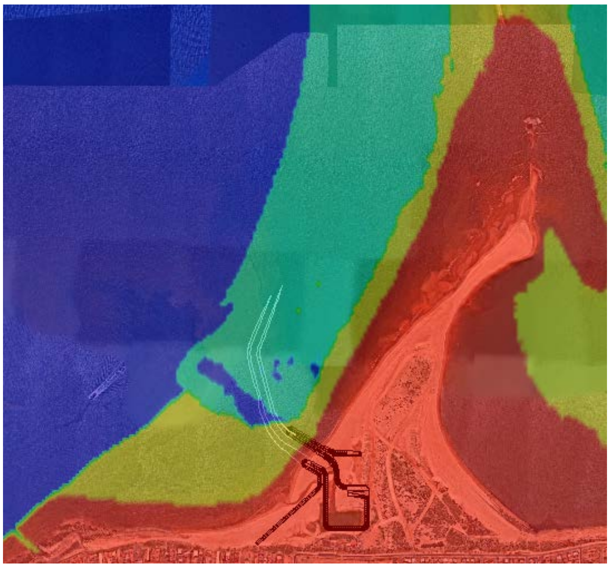


Figure 5.18: Initial Surface Sediment Type Map. Red: Fine to coarse sands with low fines content (5%), Yellow: Coarse sands with some fine sand (20%), Light Blue: Fine to coarse sands with high fines content (20%). Dark Blue: No Sediment.

An in-situ dry density of 1600 kg/m^3 was adopted for all sand fractions, while an in-situ dry density of 500 kg/m^3 was adopted for the fine sediment (silt) fraction. A review of van Rijn (2006) was undertaken to define the critical shear stress and maximum erosion rate for the defined silt fractions. Fall velocities were based on the sediment fraction particle size and adopted from data collected near the study area reported in BMT & DoT (2019). The critical shear stress for erosion was specified as 0.4 N/m^2 and the critical shear stress for deposition was specified as 0.1 N/m^2. Flocculation is not a significant process for silts or when suspended sediment concentrations are low, and salinity variations are minimal.

5.5.2 Metocean Scenarios

Sedimentation simulations were based on the following metocean scenarios:

- 2 representative monthly simulations for summer and winter conditions
- Cyclonic scenario based on the 100-years ARI event defined for metocean design criteria.

From analysis of historical Spoilbank change and modelling of potential longshore transport along the western shoreline of the Spoilbank, sediment transport in the vicinity of the SBM is dominated by episodic cyclonic events, being approximately 250% larger than ambient transport rates on an annualised basis and up to 6-7 times larger under the 100-year ARI event (see Table 5.1).

5.5.2.1 Ambient Conditions

Model simulations are based on time periods representative of typical wet and dry season conditions as defined in Section 2.6. Model simulations were undertaken for minimum 28-day period (following model warm-up) to cover two full spring-neap cycles. The simulation periods for the model were:

- Wet Season: 01/01/2019 00:00 to 28/01/2019 00:00
- Dry Season: 01/06/2019 00:00 to 01/07/2019 00:00

The following processes were quantified under ambient conditions:

- Siltation of the marina basin
- Sedimentation of the channel
- Transport / sedimentation outside the marina
- Potential for northerly transport along the shoreline

5.5.2.2 Cyclonic Conditions

To estimate sediment transport processes under cyclonic conditions, a design cyclonic scenario was selected from the metocean design criteria event set. The 100-year ARI condition, based on Monte Carlo event MC32335 (see Section 4.1), was adopted being the event deemed to have the largest sediment transport potential along the western shoreline.

5.5.3 Siltation of the Marina Basin

To provide a quantitative estimate of siltation of fines in the marina basin the results from the two seasonal simulations were combined and scaled by a factor of six to provide a representative annual estimate. Firstly, the suspended sediment concentration at the DoT AWAC locations were compared to the measured data to ensure fines in suspension were being reasonably replicated by the model. The probability distribution of SSC from the measured and modelled data is presented in Figure 5.19 showing a reasonable agreement.

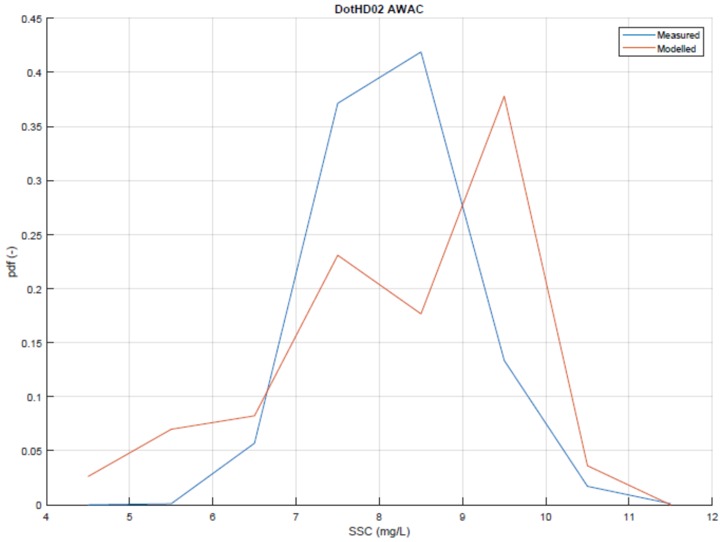


Figure 5.19: Modelled (2 months, summer and winter) vs Measured (7-months) comparison of suspended sediment concentration at DoTHD02

The resulting annual deposition map for fines in the marina basin is presented in Figure 5.20, which indicates little to no deposition of fines in the marina entrance channel and maximum deposition of up to 0.23m in the south-west and north-east corners. The lack of deposition in the entrance channel is consistent with the flow velocities generated by the tidal prism exchange. An annual deposition volume of 4,600 m^3 is estimated with marginal seasonal difference indicating slightly increased deposition in the summer period, based on limited data available to the study. There is negligible influence of channel and entrance configurations being proposed on the deposition of fines in the basin. Further, siltation under cyclonic conditions is immaterial to the annualised results as the short duration events produce only a temporary increase in background suspended sediment concentrations.

It is noted that the marina basin investigated has a constant bed level with no berth pockets, the presence of which may result in increased deposition. Further, the potential siltation resulting from suspended sediment has not taken into account a number of possible drivers, include harbour motions generated by passing vessels, resuspension due to turbulence from the revetments or transport enhanced by bed features (e.g. sand ribbons or bars).

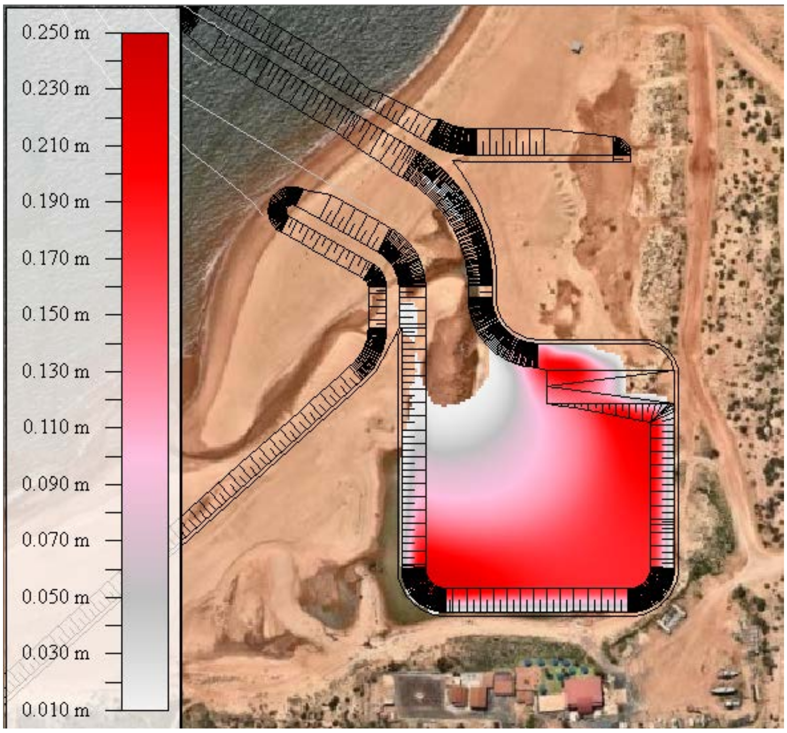


Figure 5.20: Annual Deposition Map of Fines in the Marina Basin (Siltation Depth, m)

5.5.4 Sediment Bypassing and Channel Sedimentation

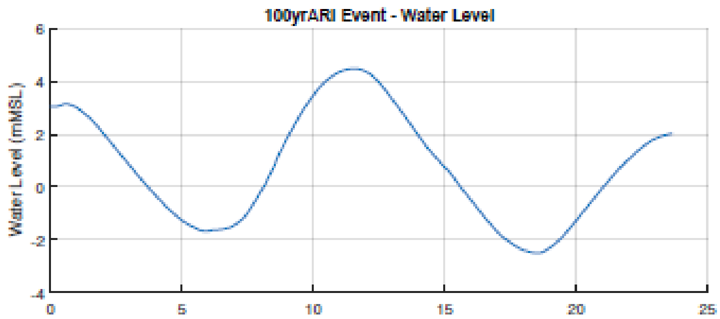
Potential channel sedimentation was assessed using both the potential longshore transport rates developed with the Litprof model (see Section 5.4) and the Deflt3D Online Sediment Transport model. As noted above, Delft3D is limited in its ability to model cross shore and longshore dynamics in the surf zone, however changes to the morphology settings and inclusion of the surface roller model improve the model outcomes. As result, the Delft3D model results were used to define the percentage of transport to bypass the northern entrance structure and subsequently applied to the longshore transport rates from Litprof to produce an estimate of potential channel sedimentation.

The Delft3D model was used to simulate the ambient and cyclonic scenarios and transport volumes extracted along two cross sections, as shown in Figure 5.22. The total transport across each cross section can then be compared to calculate the % bypass for alternate entrance structure options. A graphical example is provided in Figure 5.22 that shows the relative transport volume that bypasses the head of the entrance structure for both Layouts A and B under a 100-year ARI event. A similar analysis is completed for ambient conditions. The resulting bypass percentages (taken as an average of all simulations) can be summarised as follows:

- Layout A Entrance: 23% bypass of the northern breakwater;
- Layout B Entrance: 16% bypass of the northern breakwater;
- Layout C Entrance: 18% bypass of the northern breakwater and sand trap;

These results indicate the effectiveness of the Hook feature of the Layout B breakwater and the sand trap feature of Layout C.

Figure 5.21: Delft3D Profiles for Longshore Transport Volumes



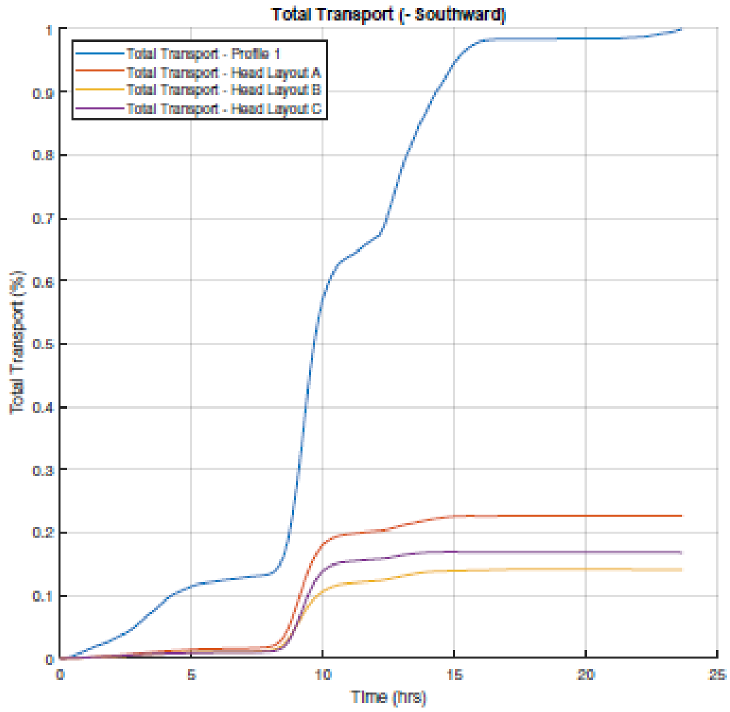


Figure 5.22: Longshore Transport (as % of event total) past Transects north of the Spoilbank Marina (Profile 1) and at the Head of the Northern Entrance Structure for Layouts A, B and C.

The percentage bypass can then be used to factor the longshore transport estimates from the Litprof modelling to provide an estimate of sediment volume that would bypass the northern breakwater and the maximum deposition under both ambient and cyclonic conditions. The results are summarised in Table 5.2 and Table 5.3.

Table 5.2: Summary of longshore transport bypass potential of the Spoilbank Northern Entrance Structure

Scenario	Net Transport (m^3 South)	Bypass Volume (m^3) Layout A	Bypass Volume (m^3) Layout B	Bypass Volume (m^3) Layout C
Ambient (Wet Season)	7,300*	1,700	1,250	1,300
Ambient (Dry Season)	10,100*	2,350	1,650	1,800
1-yr ARI	27,200	6,250	4,500	4,900
5-yr ARI	49,600	11,500	8,000	8,900
20-yr ARI	83,300	19,250	13,500	15,000
100-yr ARI	119,400	27,500	19,250	21,500
500-yr ARI	158,300	36,500	25,500	28,500
Annualised	49,800	11,500	8,000	9,000

* Seasonal estimates are 6-month equivalent values of net transport volumes.

Table 5.3: Summary of Maximum potential deposition in the Spoilbank Marina Entrance Channel results from longshore transport bypassing the Northern Entrance Structure.

Scenario	Maximum Deposition (m)		
	Layout A	Layout B	Layout C
Ambient (Wet Season)	0.1	0.1	0.1
Ambient (Dry Season)	0.2	0.1	0.2
1-yr ARI	0.5	0.4	0.4
5-yr ARI	1.0	0.7	0.8
20-yr ARI	1.6	1.1	1.3
100-yr ARI	2.3	1.6	1.8
500-yr ARI	3.0	2.2	2.4
Annualised	0.9	0.7	0.8

* Seasonal estimates are 6-month equivalent values of net transport volumes.

However, the above assessment of bypass potential assumed that the sediment trap, along the shoreline to the north of the entrance structures is empty with the shoreline in its current position. Over time, longshore transport volumes will be trapped in this area and without regular maintenance the shoreline is expected to accrete towards the head of the breakwater. The effect of the sediment trap being full prior to a large cyclone event was also investigated, with an assumed shoreline position as presented in Figure 5.23. The resulting relative transport volume that bypasses the head of the entrance structure for Layouts A, with an empty and full sediment trap, under a 100-year ARI event is presented in Figure 5.24, showing a large increase in the bypass potential of up to 43% when the sediment trap is full prior to the event. The accreted shoreline provides a more efficient sediment transport pathway to the end of the breakwater. This is an almost doubling of the bypass potential and highlights the importance of maximising the trapping potential of the sediment trap through regular maintenance to reduce bypassing potential.

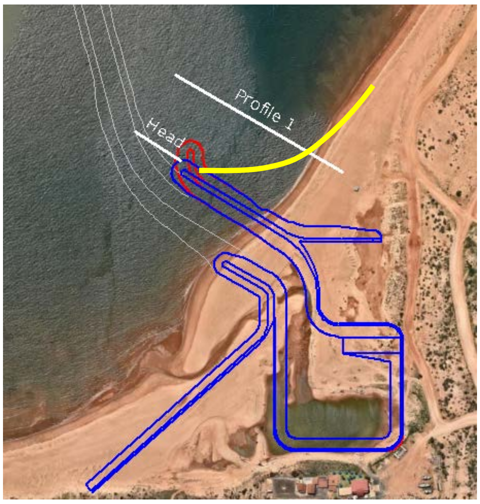


Figure 5.23: Assumed shoreline alignment (yellow) depicting a full sediment trap to the north of the Marina entrance.

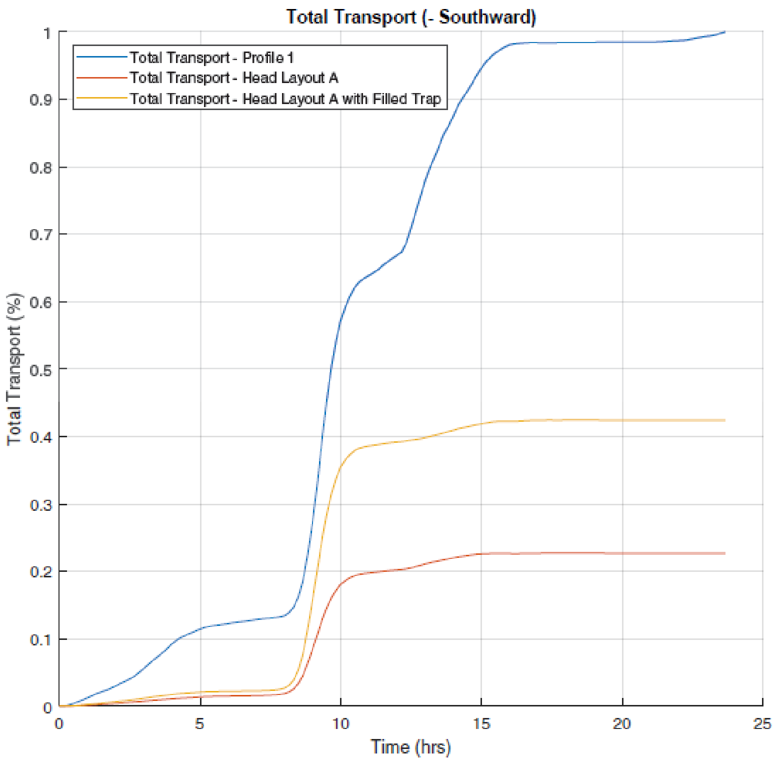


Figure 5.24: Longshore Transport (as % of event total) past Transects north of the Spoilbank Marina (Profile 1) and at the Head of the Northern Entrance Structure for Marina Layout A with an empty and filled sediment trap.

Distribution of the sedimentation in the channel is variable and most pronounced in the channel adjacent the head of the northern entrance structure. Indicative sedimentation maps of the entrance channel are presented in Figure 5.25, Figure 5.26 and Figure 5.27 for Marina Layout A, B and C, respectively. It could be expected the maximum deposition in the entrance channel will be between 0.5 and 3m annually, dependent of the occurrence and severity of tropical cyclones in a given year. For the outer channel section, a deposition rate in the range 0.2m to 0.5m per year is predicted based on the modelling.

It is also likely that over time erosion of the shoreline to the South West of the SBM entrance will occur as the predominantly southward transport along the western shoreline of the Spoilbank is interrupted by the breakwater structures and entrance channel. This is evident in the modelling (see Figure 5.25) and could be expected to become pronounced over the course of 2 to 5 years.

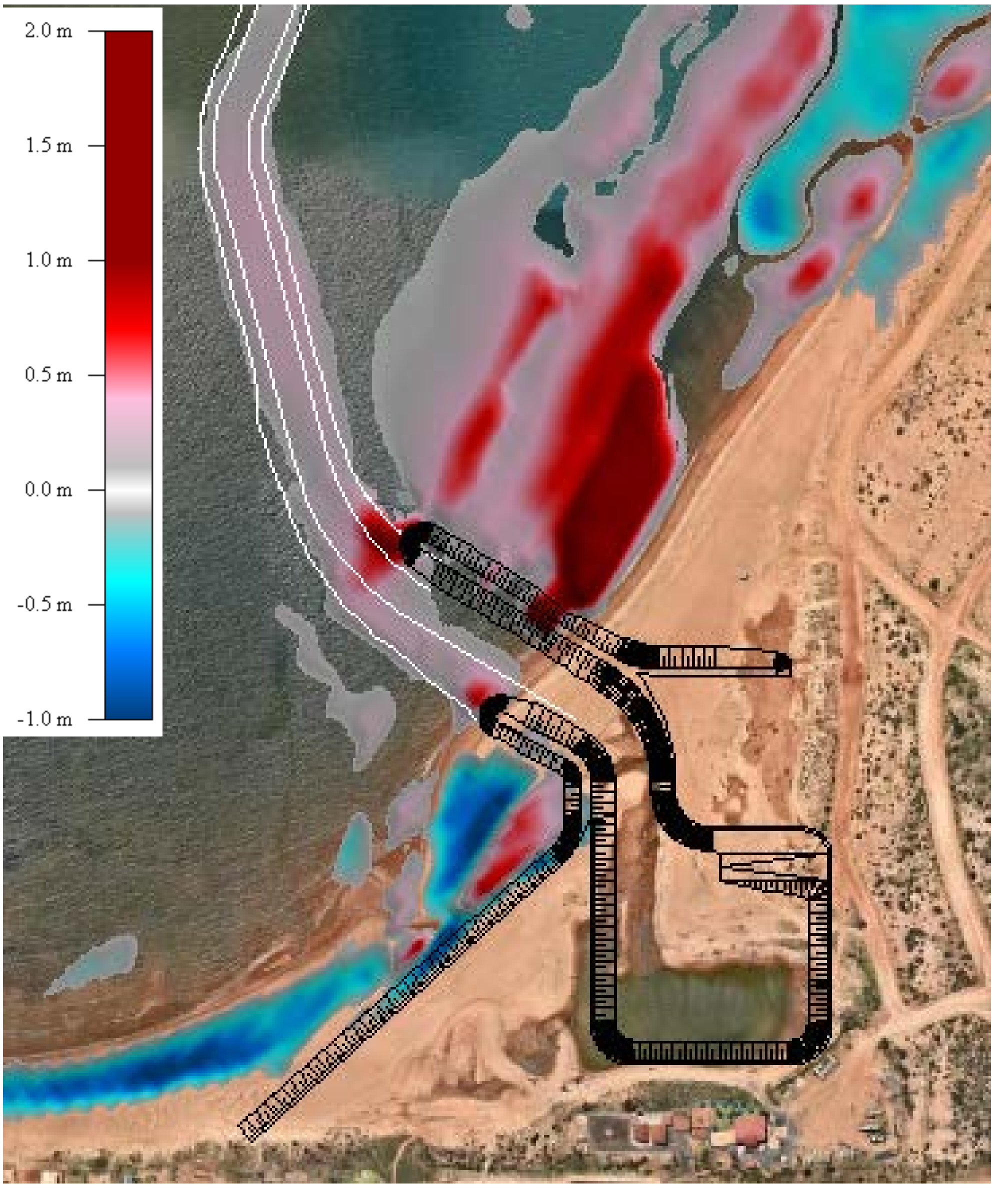


Figure 5.25: Sedimentation Map of the Marina Layout A entrance channel normalised to the annualised estimates of longshore sediment transport. Red indicates deposition, Blue indicates erosion.

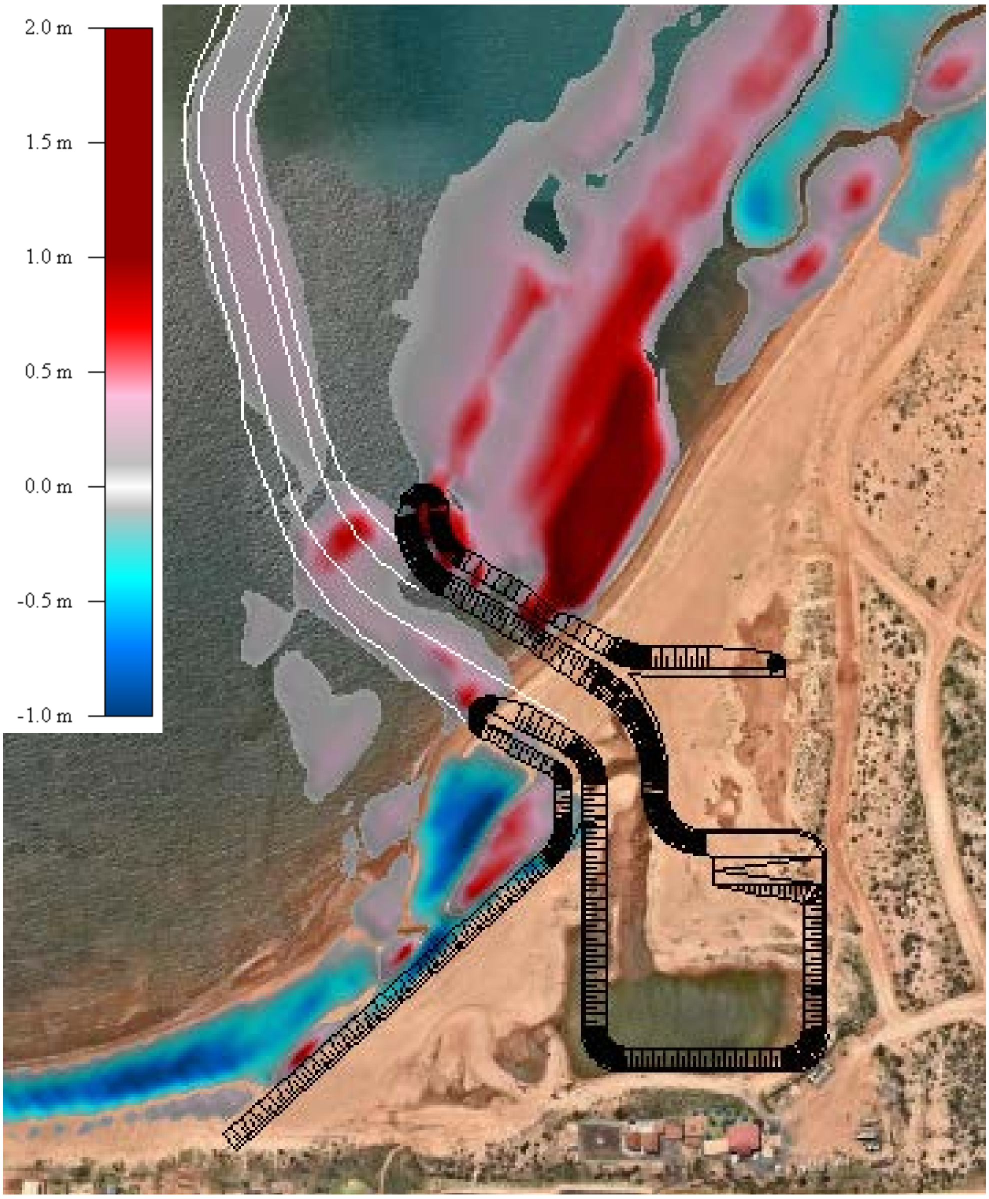


Figure 5.26: Sedimentation Map of the Marina Layout B entrance channel normalised to the annualised estimates of longshore sediment transport. Red indicates deposition, Blue indicates erosion.

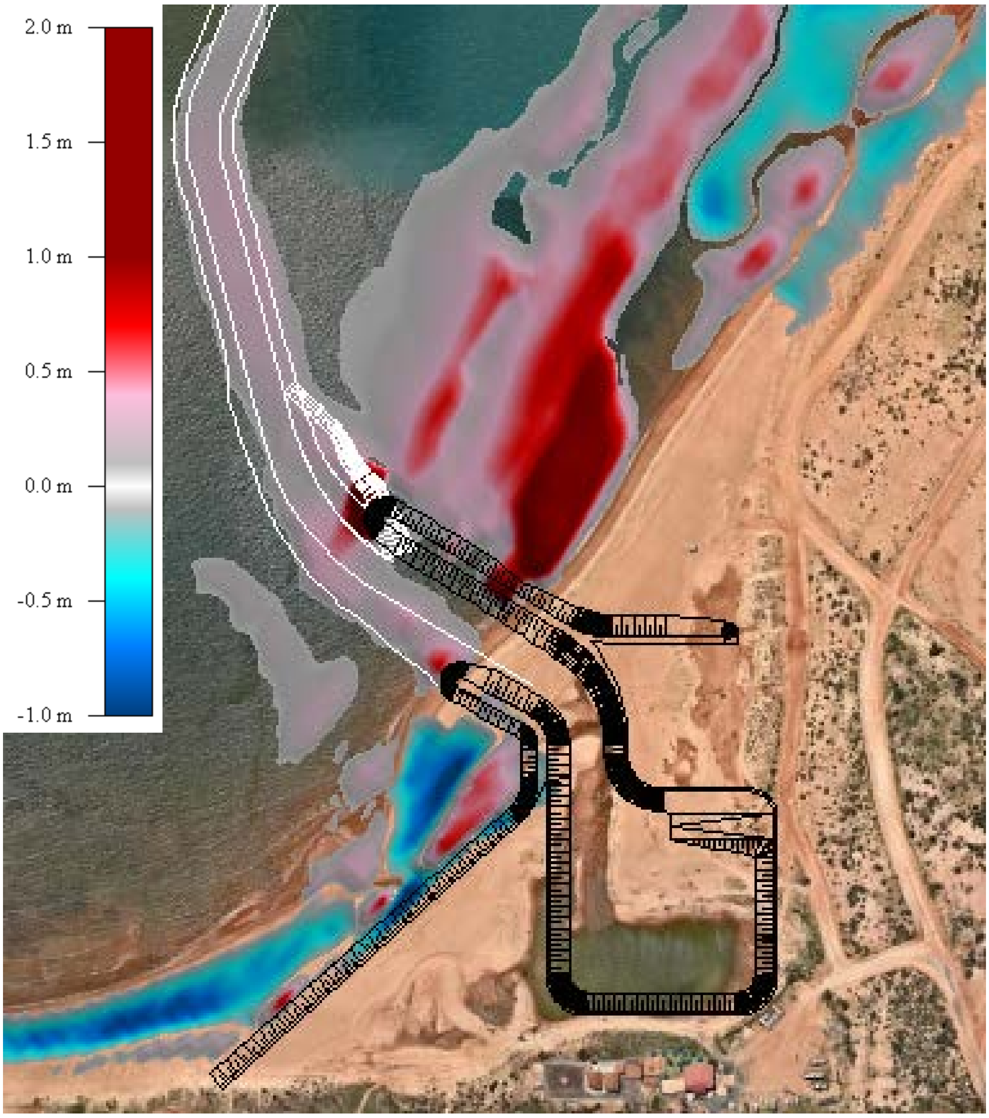


Figure 5.27: Sedimentation Map of the Marina Layout C entrance channel normalised to the annualised estimates of longshore sediment transport. Red indicates deposition, Blue indicates erosion.

5.5.5 Northward transport potential

The longshore transport modelling, summarised in Table 5.1, indicated that net sediment transport potential under both ambient and cyclonic conditions is southward. However, the construction of the marina will impact on the local hydrodynamics and any potential for northward transport may result in channel sedimentation from the south. To assess this potential the bed shear stresses from the modelling were assessed. The driver for sediment transport is bed shear stress, generated through the combination of the tidal and storm surge flows and wave conditions. Timeseries of combined bed shear stress was extracted from the model simulations at two locations on the south side of the SBM entrance and channel alignment, as shown in Figure 5.28.

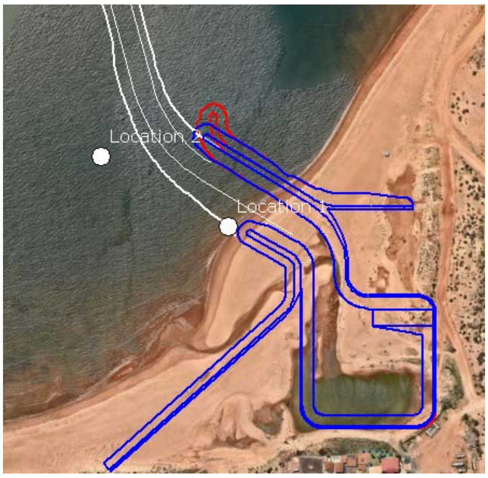


Figure 5.28: Location of Bed Shear Stress Analyses

The scatter plot of bed shear stresses (X vs Y direction) then provides an indication of the direction of sediment transport potential, which is presented in Figure 5.29 (cyclonic) and Figure 5.30 (ambient). Within Figure 5.29 and Figure 5.30, bed shear stresses greater than 1 N/m^2 (total magnitude) are shown in red, noting that the initiation of motion for sands in the presence of fines (i.e. sand / mud mixtures) are typically increased (above 1 N/m^2 dependent on fines content). The position away from the midpoint (0,0) can be interpreted as the direction going to of the bead shear stress. As such there is very little potential for northward sediment transport to occur once the SBM marina is constructed that would result in sedimentation of the entrance channel.

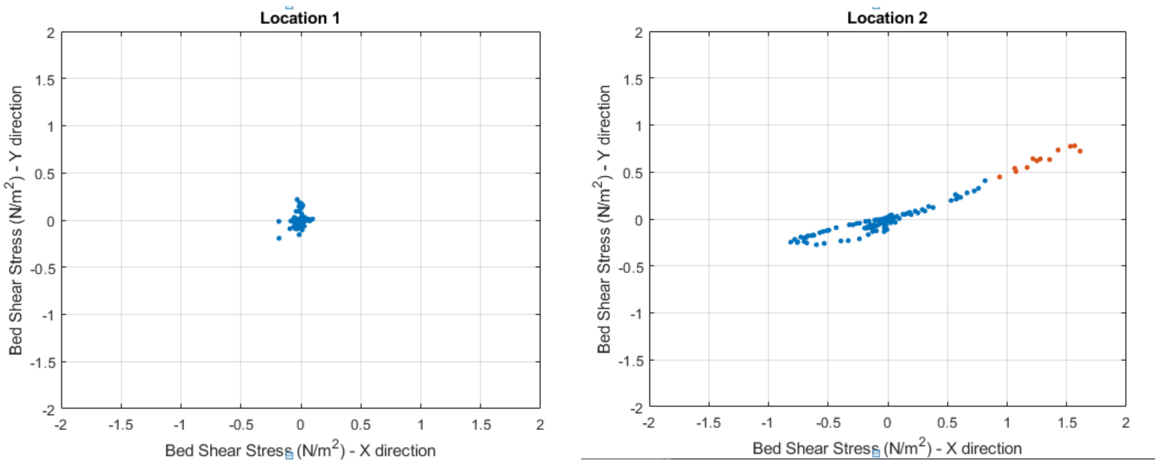


Figure 5.29: Scatter Plots of Bed Shear Stress (combined tides and waves) during the 100-year ARI cyclonic condition for Locations 1 and 2 (see Figure 7). Records with shear stress greater than 1N/m^2 marked in red.

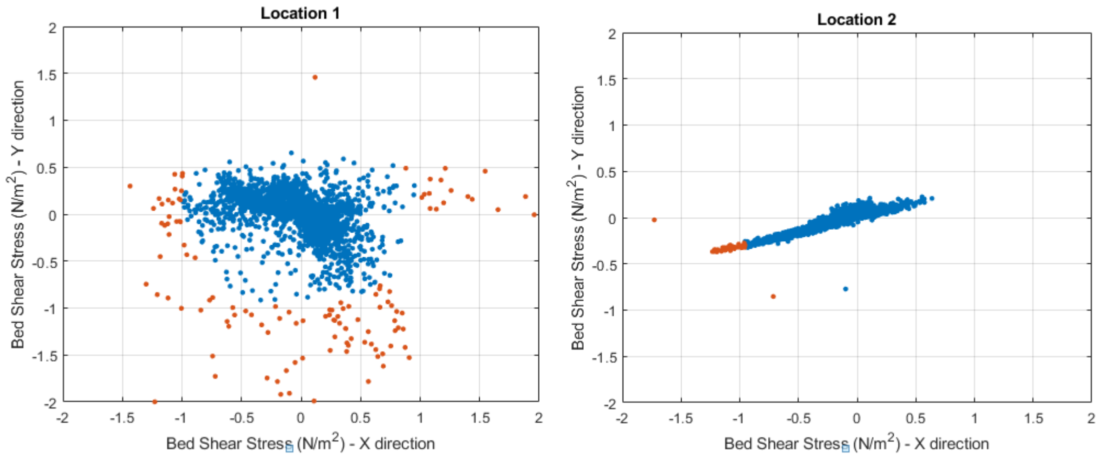


Figure 5.30: Scatter Plots of Bed Shear Stress (combined tides and waves) during ambient conditions for Locations 1 and 2 (see Figure 7). Records with shear stress greater than 1N/m^2 marked in red.

5.6 Qualifications

Estimates of sediment transport volumes, sedimentation and siltation depths presented in this report should be interpreted with consideration of the uncertainty associated with methods and analyses completed. While the numerical models and analysis outcomes have been validated and benchmarked were possible, uncertainty remains due to the following:

- Accuracy of the empirical and process-based sediment transport models. It is not uncommon to associate an uncertainty range of up for +/-50% for process-based modelling of sediment transport, particularly where no validation has been completed.
- The design event methodology and selection of discrete events to estimate sediment transport under cyclonic conditions.
- The selection of representative months to estimate ambient transport rates.
- The characterisation of the seabed composition based on available sediment data.

The methodology applied in this study has not relied on any one method or model to derive these estimates and in doing so has benchmarked the outcomes against measured seabed changes resulting from Tropical Cyclone Veronica. Given the comparisons to these measured data, an uncertainty of +/-20% in the sediment transport rates and sedimentation depths is considered appropriate. It should be noted that such uncertainty is within the range that will be expected as a result of variability in the severity and frequency of cyclone events in a given year.

6. Concluding Remarks

Baird Australia (Baird) have completed a coastal processes assessment for a proposed Spoilbank Marina on behalf of the Department of Transport (DoT). The proposed site is located at the southwest corner of the Port Hedland Spoilbank, adjacent to the existing Port Hedland Yacht Club.

The Pilbara coastline is the most cyclone-prone region of the Australian mainland, with the area immediately surrounding Port Hedland having the highest frequency of Category 4 and 5 cyclones that make landfall. Approximately 3 cyclones per year, on average, influence the metocean conditions at Port Hedland. Events of this magnitude govern the design criteria for engineering works in the Port Hedland region, including design wave heights and water levels.

A significant amount of historical information was available from the site including a range of measured data sources. Metocean data, collected by the Pilbara Port Authority (PPA), Bureau of Meteorology (BoM) and DoT, was made available for this project and provides a description of the site specific metocean conditions.

The design options for the SBM were developed by DoT and refined by marine engineering specialist, M P Rogers and Associates. The marina concept includes a basin of approximately 160 x 170m in dimension that will accommodate up to 80 vessels of sizes between 10 and 20m in length.

Three marina layouts have been assessed:

- Base Case Marina Layout (Base Case);
- Breakwater Hook Design (Option 1), and
- Base Case with Siltation Trap (Option 2)

Two entrance alignments were also investigated.

The following numerical models and datasets have been applied in the SBM investigations:

- Baird's Monte Carlo cyclone track model;
- Baird's Cyclone Windfield (CycWind) model;
- Shelf-scale Hydrodynamic model (Delft-FM);
- Shelf-scale Spectral Wave model (WW3);
- Local-scale Coupled Hydrodynamic and Spectral Wave model (Delft3D FWF); and
- Local-scale Phase Resolving (Bousinesq) Wave model (MIKE21-BW).

Validation of the numerical model systems and methods has focussed on hydrodynamic and wave conditions that were observed during a metocean data collection deployment completed by the DoT between December 2018 and June 2019. This included observations of TC Veronica, in March 2019, which has been used as a key event in the validation of models under extreme cyclonic conditions.

Cyclonic metocean design criteria were developed out to the 500-year ARI for the Port Hedland SBM project. This required a suitable cyclone event set that extends the historical record with simulated events using a stochastic-based modelling approach. Baird's Australian Tropical Cyclone Database, equivalent to a 10,000-year period, includes a total of approximately 120,000 synthetic events across the Australian cyclone region with 28,096 synthetic events that track within 200km of the coast of the Australian mainland in the northern West Australian region. Design criteria at lower return periods of 1 and 5-years ARI were also developed for design tasks for which the available measured data was utilised to complete an extreme value analysis to define the winds, waves and water levels.

The location of the development and the existing extent and orientation of the Spoilbank afford the Spoilbank Marina some protection from extreme wave conditions, with nearshore areas relatively shallow thereby limiting peak wave heights which are highly correlated to water levels. Metocean design criteria made account of all nearshore processes.

Assessments of hydrodynamic and waves post-development has also been completed to quantify the potential change in coastal processed as a result of the marina development. In general, the marina concepts that were assessed will cause only local changes to the hydrodynamic and wave regime on the western side of the Spoilbank. However, the following is noted and should be considered during detailed design:

- under both ambient and cyclonic conditions, increases in metocean conditions (currents and waves) are predicted with a concentration of flows and waves on the head of the northern entrance breakwater.
- peak storm water levels including wave setup, would generate inundation past the extent of the proposed revetment along the northern edge of the marina development, assuming existing Spoilbank levels north of the marina are maintained.
- Wave propagation to the marina location is significantly influenced by the flat, shallow seabed and the presence of dredged channels (including the marina entrance channel). Modelling of post-development cyclonic wave conditions identified that Channel Option 2 affords greater protection of the marina entrance than Channel Option 1.

The sediment transport study investigated the following:

- Dynamics of the sand trap and entrance channel;
- Anticipated sedimentation of the approach channel;
- Potential sedimentation of the harbour basin;
- Alongshore sediment transport associated with progressive migration of the Spoilbank.

Key outcomes from the sediment transport investigations include:

- The Spoilbank is an artificial low sand spit feature parallel to the Goldsworthy channel in Port Hedland formed by the sidecasting from material disposed from dredging the Port Hedland navigational channel between 1965-1970. An analysis of shoreline positions has demonstrated three phases of Spoilbank evolution with a stable shoreline position being achieved in the mid-1990s following a period of growth and a clear erosional trend starting around 2003.
- A conceptual sediment transport model was derived and found the predominant transport processes to be southerly longshore transport and overwash of the land mass, mainly driven by severe episodic cyclonic events. With the dominant southerly drivers for sediment transport and absence of a sediment source to replenish Spoilbank, the mechanisms for continued rotation of the westerly shoreline and loss of the Spoilbank landmass is clear. Any development on the Spoilbank will need to account for the significant and ongoing loss of land over the design life of the project.
- Previous estimates of longshore transport ranged from 6,000 to 19,000m^3/yr under ambient conditions and 30,000 to 40,000m^3 per cyclone event (on average), along the western shoreline. Modelled results, benchmarked against recent measurements of shoreline change during TC Veronica (March 2019), suggest that an annualised longshore transport rate of between 40,000 and 50,000m^3/yr may be expected but will vary depending on the severity and frequency of tropical cyclone events. As such the range of longshore sediment transport in any given year could reasonably be between 15,000 and >100,000m^3.
- The northern breakwater structure of the Spoilbank Marina will act as a sediment trap capturing a large portion of the southerly transport along the western shoreline. However, bypassing of the northern breakwater will occur and depending on the structure/channel configuration selected, up to 24% of the longshore transport could bypass the structure and deposit in the entrance channel. This estimate assumes the sediment trap has sufficient capacity to store the trapped sediment and should this not be the case, the bypass potential of the northern structure could double. Regular maintenance of the sediment trap will be important in maximising the trapping potential of the sediment trap to reduce bypassing of sediment into the entrance channel.

- Deposition rates in the entrance channel are estimated to be between 0.5 and 3m annually, dependent of the occurrence and severity of tropical cyclones in a given year. For the outer channel section, a deposition rate in the range 0.2 to 0.5m per year is predicted based on the modelling.
- A background deposition of fine sediments will continually occur resulting in up to 0.25m of deposition (local) due to background concentrations of suspended sediments in the area.

While the location is afforded some protection from extreme cyclonic conditions and provides a relatively calm ambient metocean climate for a marina development the management of sediment will be a key operational task to ensure the successful functioning of the marina facility.

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Appendix A

Metocean Data Summary

A.1 Metocean Data Summary

Metocean data, collected by both the Pilbara Port Authority (PPA) and DoT, was made available over approximately 27-week period between December 2018 and July 2019. Metocean parameters for water levels, waves, currents and winds were provided across 10 locations, including:

- Port Beacon C2 (PPA) – Waves (DWR)
- Port Beacon 15 (PPA) – Waves (DWR)
- Port Beacon 16 (PPA) – Waves, Currents (AWAC), Winds (Met Station)
- Port Beacon 17 (PPA) – Water Level (Tide Gauge)
- Port Beacon 31 (PPA) - Water Level (Tide Gauge)
- Port Beacon 47 (PPA) – Waves, Current (AWAC), Water Level (Tide Gauge)
- Port Hedland Tower (PPA) – Wind (Met Station)
- HD01 (DoT) – Waves, Water Level, Currents (AWAC)
- HD02 (DoT) – Waves, Water Level, Currents (AWAC)
- Port Hedland Airport (BoM) – Wind (Met Station)

The locations of the metocean measurements is presented in Figure 3.

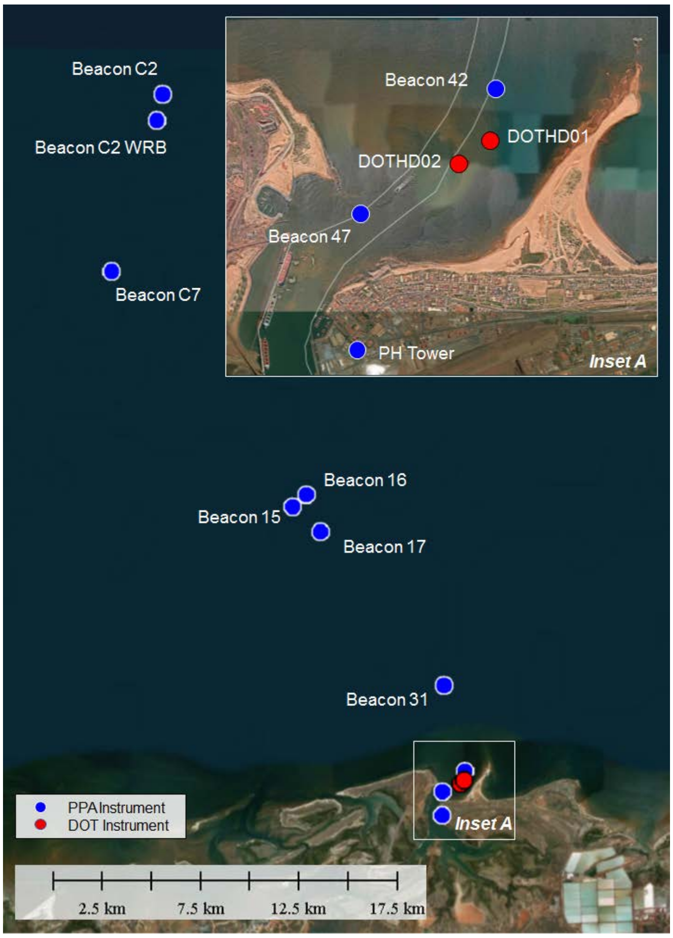


Figure 7.1: Location of Metocean Measurements from PPA and DoT

A.1.1 DoT Data

Data return from the DoT's instruments (HD01 and HD02) is good. Water level, current (magnitude and direction) and wave data at both locations appear of good quality.

A.1.2 PPA Data

Dropouts in the measurement of water levels were evident in the data provided by at Port Beacons 17 and 31, with the most notable dropouts occurring over the period of TC Veronica (23-26 March 2019). Water level data at Port Beacon 47 (closest PPA tide gauge closest to the Spoilbank Marina location) appears reasonable and as expected.

Current data (magnitude and direction) from the PPA appears of reasonable quality over the measurement period, albeit with some missing data during January 2019 and over the period of TC Veronica at Port Beacon 16. Data at Port Beacon 47 indicates elevated current magnitudes over the period of TC Veronica. Note that due to lack of metadata, it is assumed the reported currents are depth-averaged and not at a particular level above the seabed (e.g. at the surface).

Wave data from the PPA appears of reasonable quality with a good return of data over the measurement period at Port Beacons 2, 15 and 47. There are extended periods of no data at Port Beacon 16, particularly over periods of elevated wave heights. It is noted that the quality of data at Port Beacon 47 is suspect for many records, with wave heights greater than offshore locations, unrealistically large wave periods and a high scatter in the reported directions. As such, this data should be treated with caution and requires a thorough quality check. Fortunately, suspect data over the TC Veronica period appears limited, however wave periods at Port Beacons 2 and 15 are unrealistic at times. Note that wave data from the PPA was provided as sea and swell partitions, and the total wave height was calculated by summation of the energy of each partition (i.e. H2).

Wind data from the PPA's Port Hedland Tower is measured at 40.5m above ground level, so has been adjusted to be reported at a standard 10m above ground level. This dataset is continuous and appears to be of reasonable quality.

A.1.3 BoM Data

Data return from the BoM is good, with note given to the change in measurement method evident in 1994 and again in 2000. This change in measurement style has increased the number of directional bins at which the wind can be measured, as shown in the timeseries plot in Appendix A.

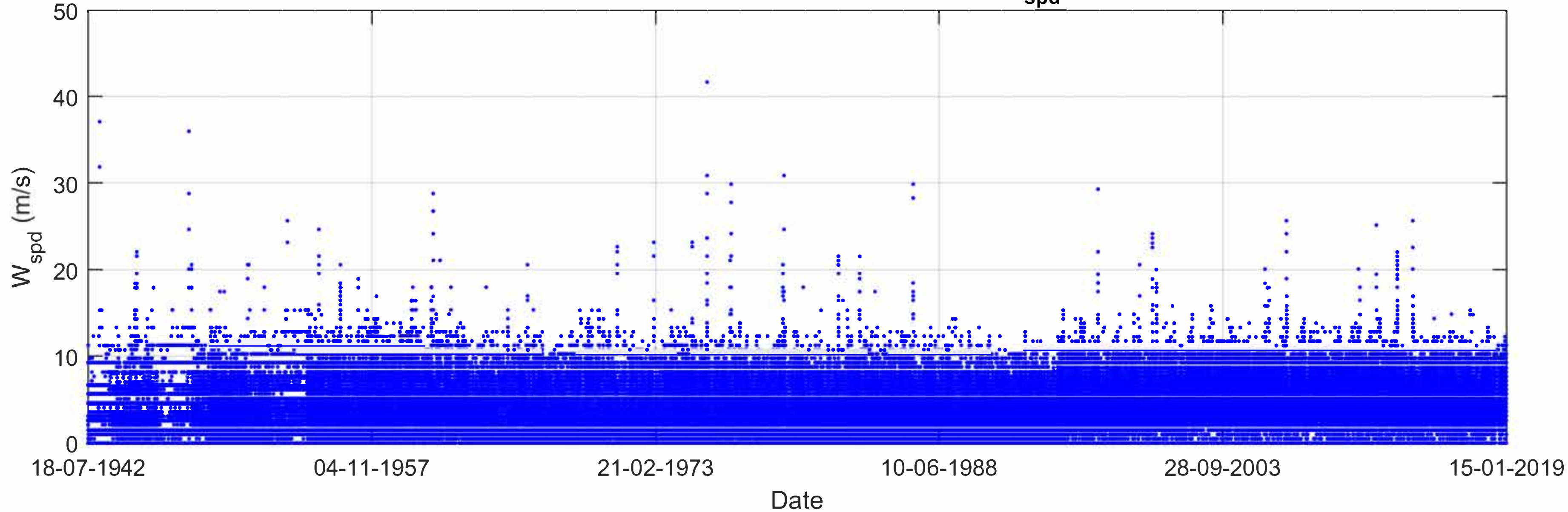
With a lack of detailed metadata, the following assumptions have been made:

- Water Levels
  - DoT water level data has been reduced to MSL as calculated over the duration of the deployment.
  - PPA water level datum is Chart Datum that is specific to each location. Chart Datum information at Port Beacons 17 and 31 has not been provided (Port Beacon 47 assumed same as the Port CD).
- Currents
  - PPA current data is assumed to be depth averaged.
- Waves
  - The sea-swell split on the DoT wave data uses an 8 second split.
  - PPA wave data is provided as sea and swell based on an 8 second split. Total wave height has been calculated by summation of the sea and swell energy.

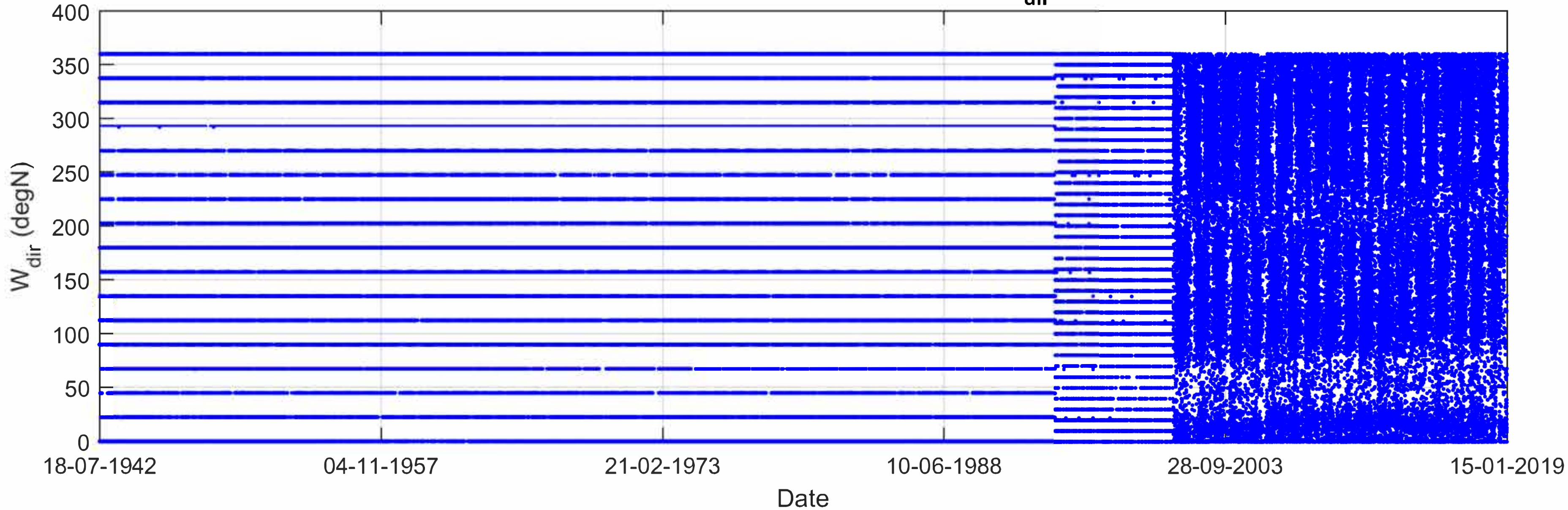
Appendix B

Numerical Model Validations

Port Hedland Airport 04032 - BOM Measured W_{spd} (m/s)

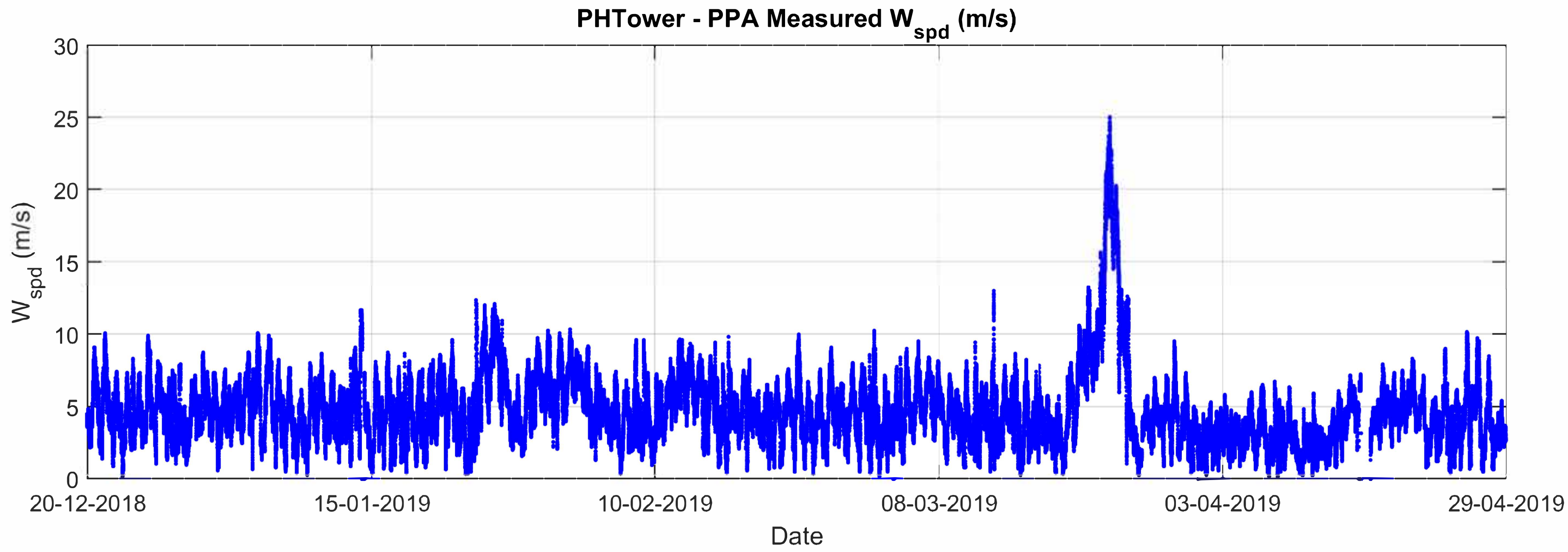


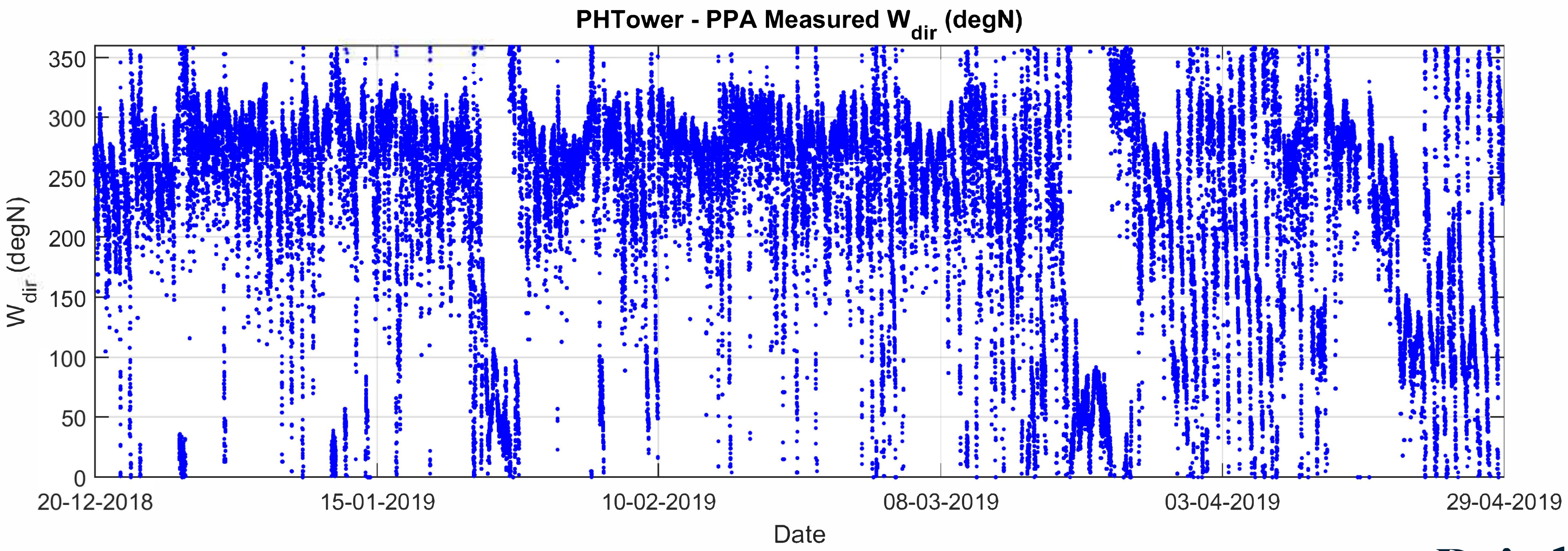
Port Hedland Airport 04032 - BOM Measured W_{dir} (degN)

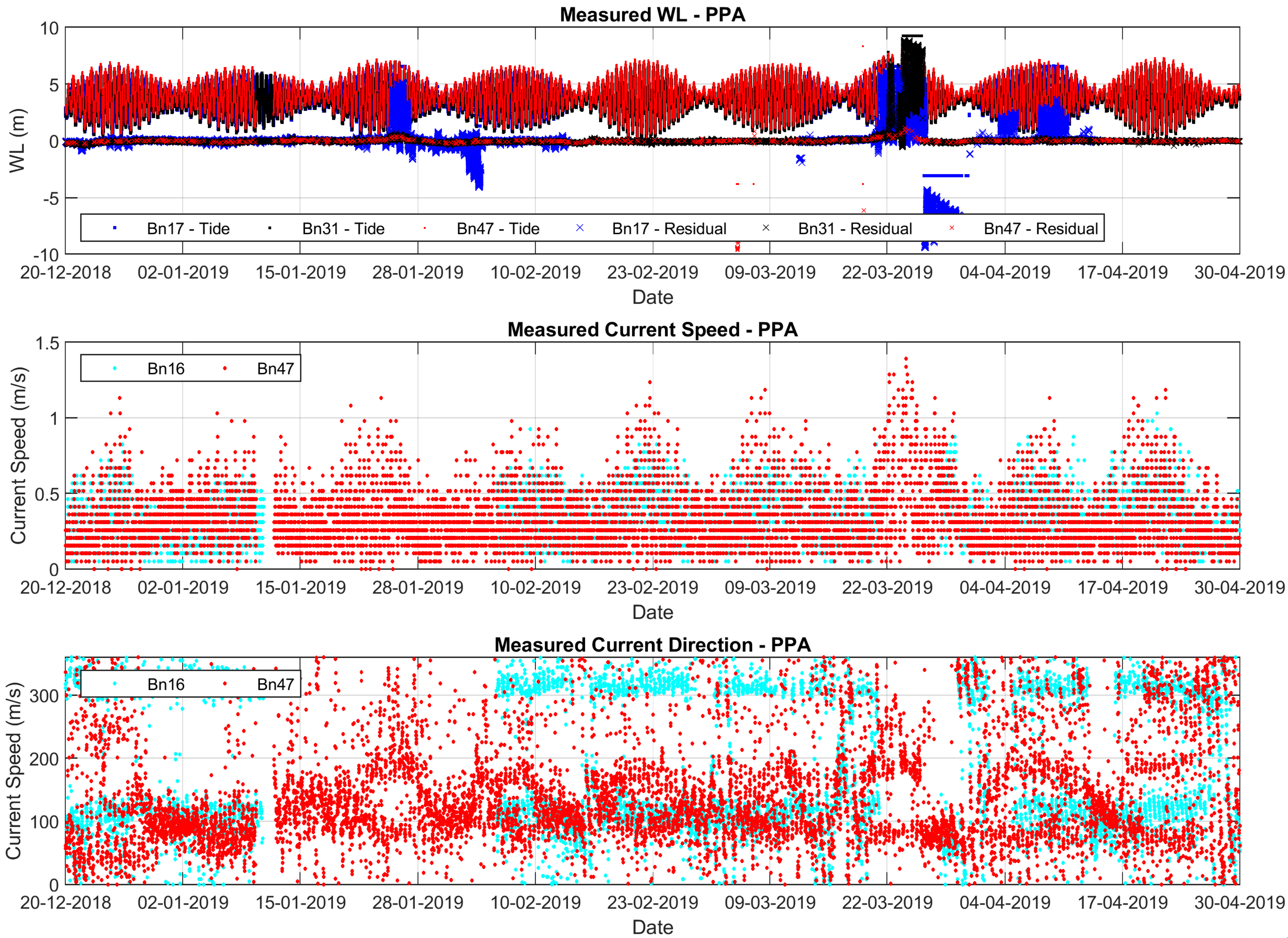


13143.101 | 07-Jun-2019
.\Figures\PHAirport04032_Wind_TimeSeries.fig

Baird.

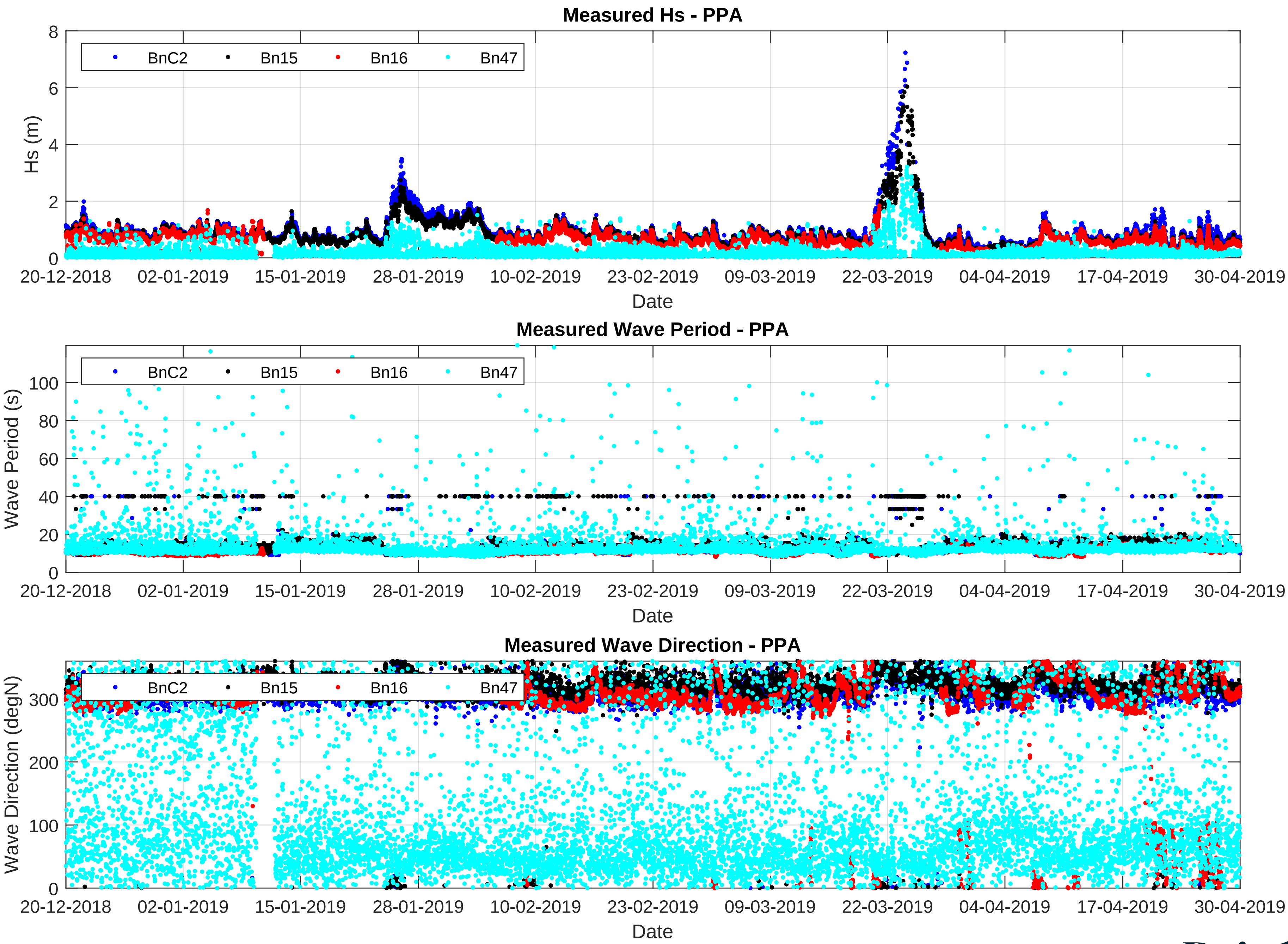

PHTower - PPA Measured W_{spd} (m/s)
W_{spd} (m/s)
30
25
20
15
10
5
0
20-12-2018
15-01-2019
10-02-2019
08-03-2019
03-04-2019
29-04-2019
Date

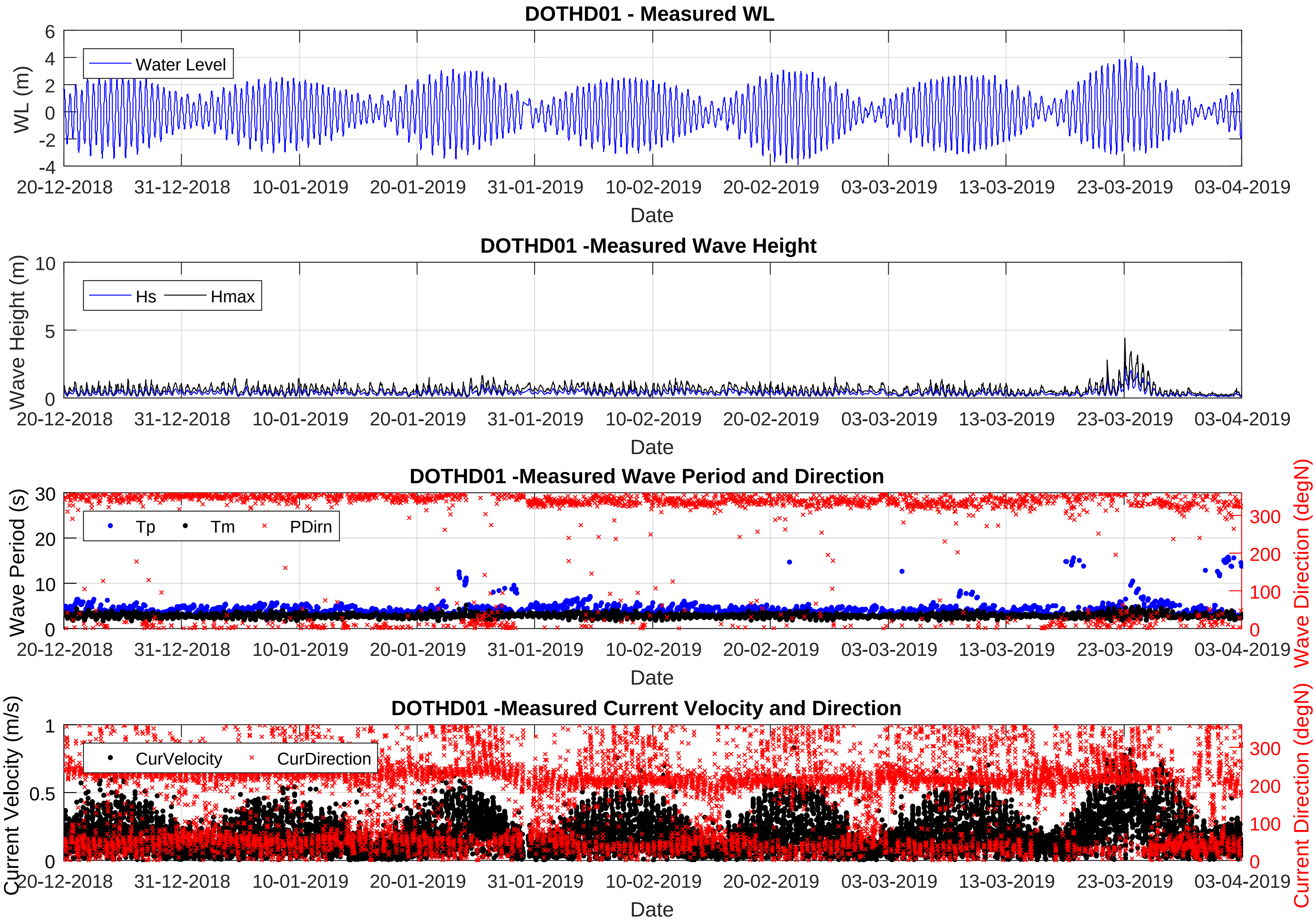

PHTower - PPA Measured W_{dir} (degN)
W_{dir} (degN)
350
300
250
200
150
100
50
0
20-12-2018
15-01-2019
10-02-2019
08-03-2019
03-04-2019
29-04-2019
Date



13143.101 | 17-Jun-2019
N:\13143.101_DoT_SpoilbankMarina\05_Analyses\MetoceanData\CompositePlots\PPA_MeasuredData_WL_Cur.pdf

Baird.

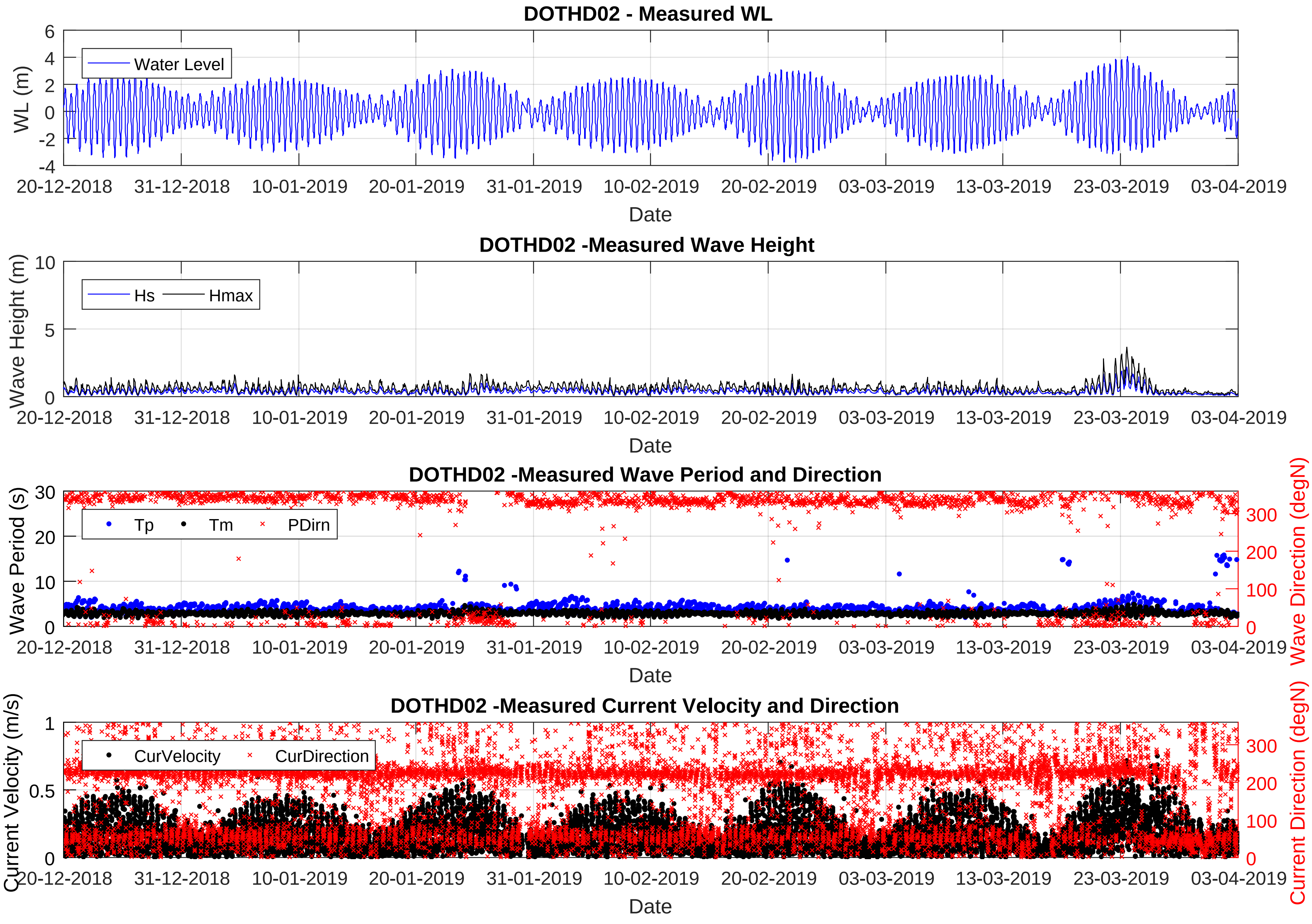

Measured Hs - PPA
BnC2
Bn15
Bn16
Bn47
Hs (m)
0
2
4
6
8
Date
Measured Wave Period - PPA
Wave Period (s)
0
20
40
60
80
100
Measured Wave Direction - PPA
Wave Direction (degN)
0
100
200
300
20-12-2018
02-01-2019
15-01-2019
28-01-2019
10-02-2019
23-02-2019
09-03-2019
22-03-2019
04-04-2019
17-04-2019
30-04-2019



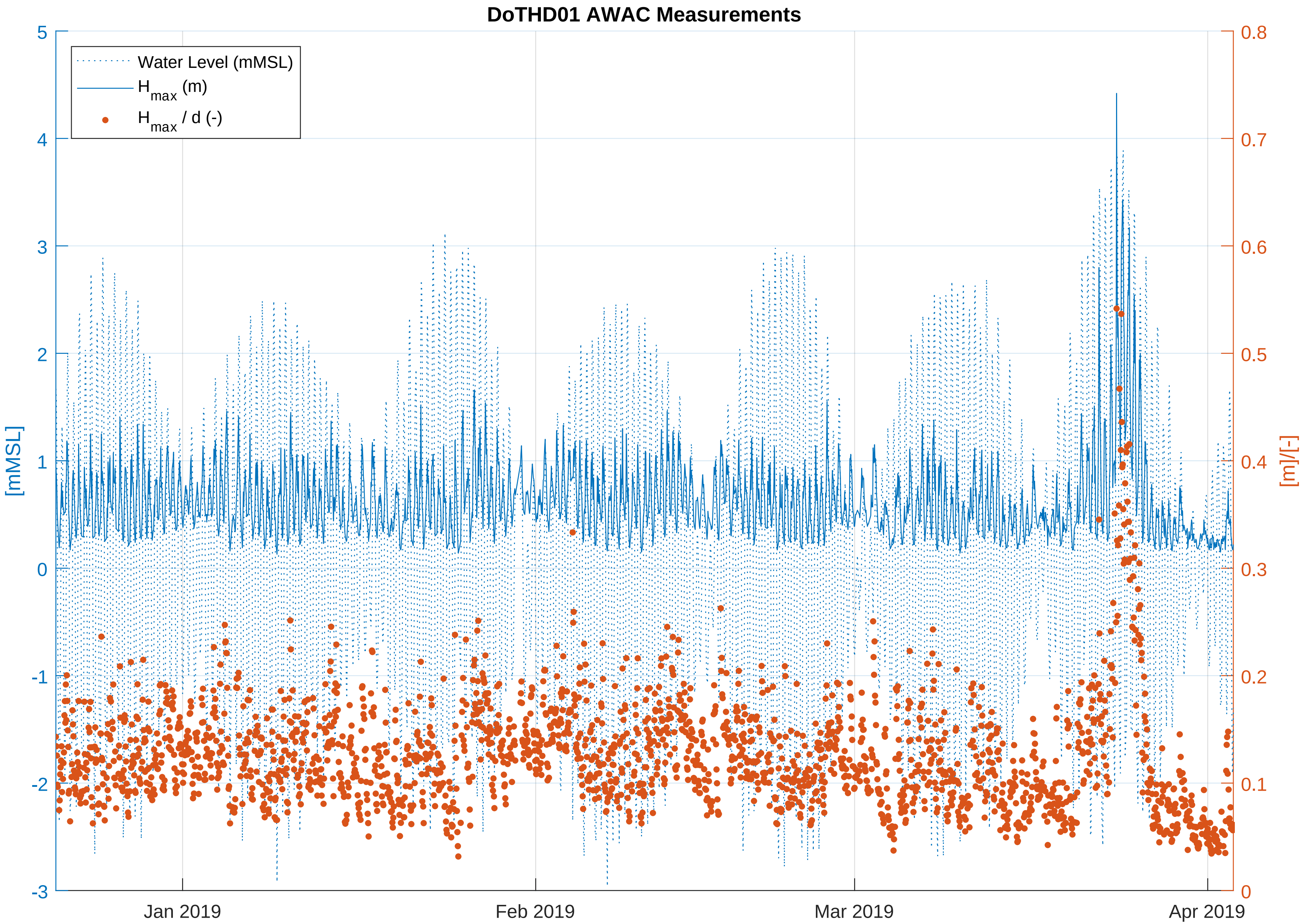
Baird.

13173.101 | Aug-2019

N:\Projects\13143.101_DoT_SpoilbankMarina\05_Analyses\MetoceanData\CompositePlots\DOTHD01_MeasuredData_reprocessed.fig

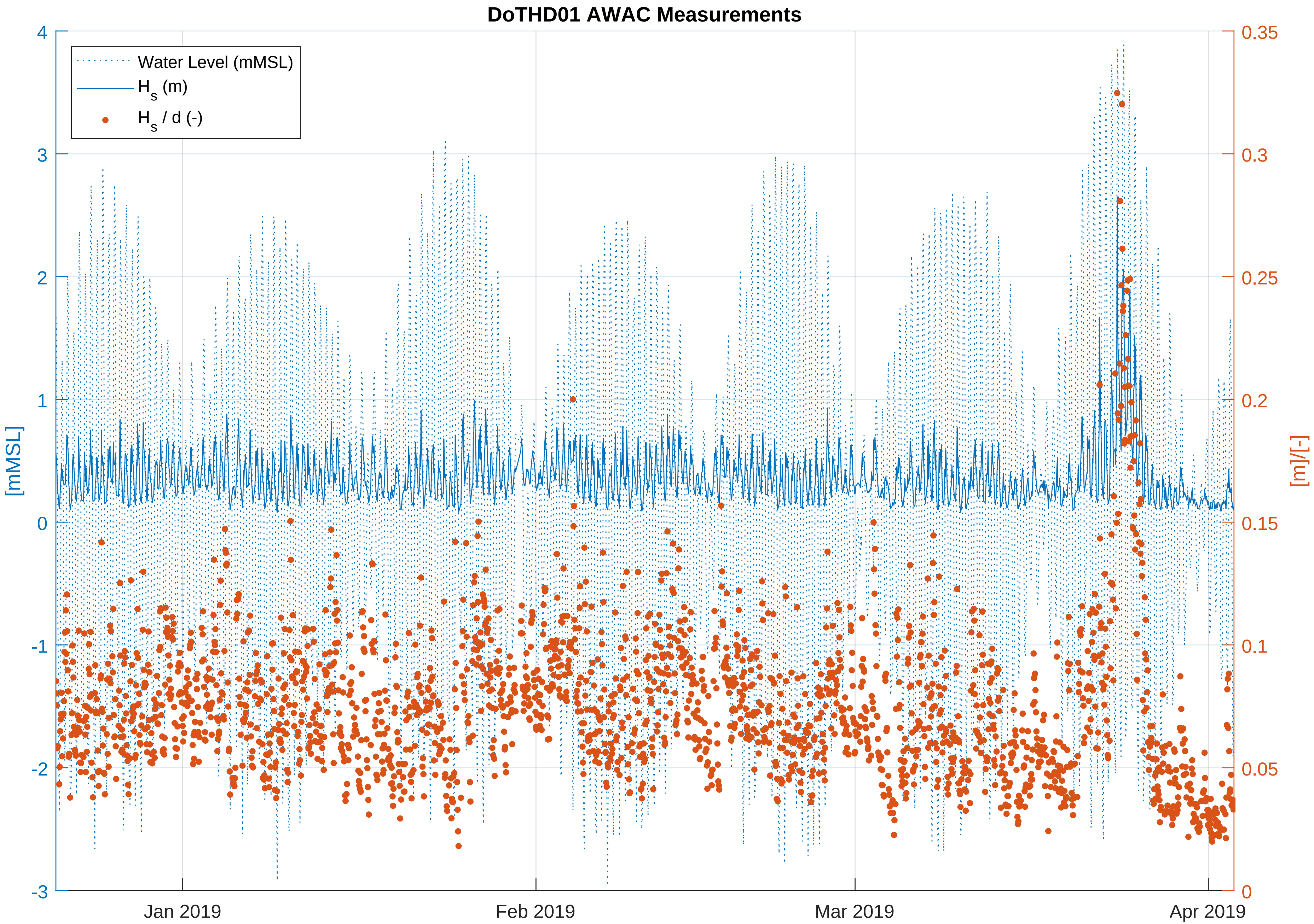


DOTHD02 - Measured WL
Water Level
WL (m)
Date
DOTHD02 -Measured Wave Height
Hs
Hmax
Wave Height (m)
Date
DOTHD02 -Measured Wave Period and Direction
Tp
Tm
PDirn
Wave Period (s)
Wave Direction (degN)
Date
DOTHD02 -Measured Current Velocity and Direction
CurVelocity
CurDirection
Current Velocity (m/s)
Current Direction (degN)
Date
20-12-2018
31-12-2018
10-01-2019
20-01-2019
31-01-2019
10-02-2019
20-02-2019
03-03-2019
13-03-2019
23-03-2019
03-04-2019

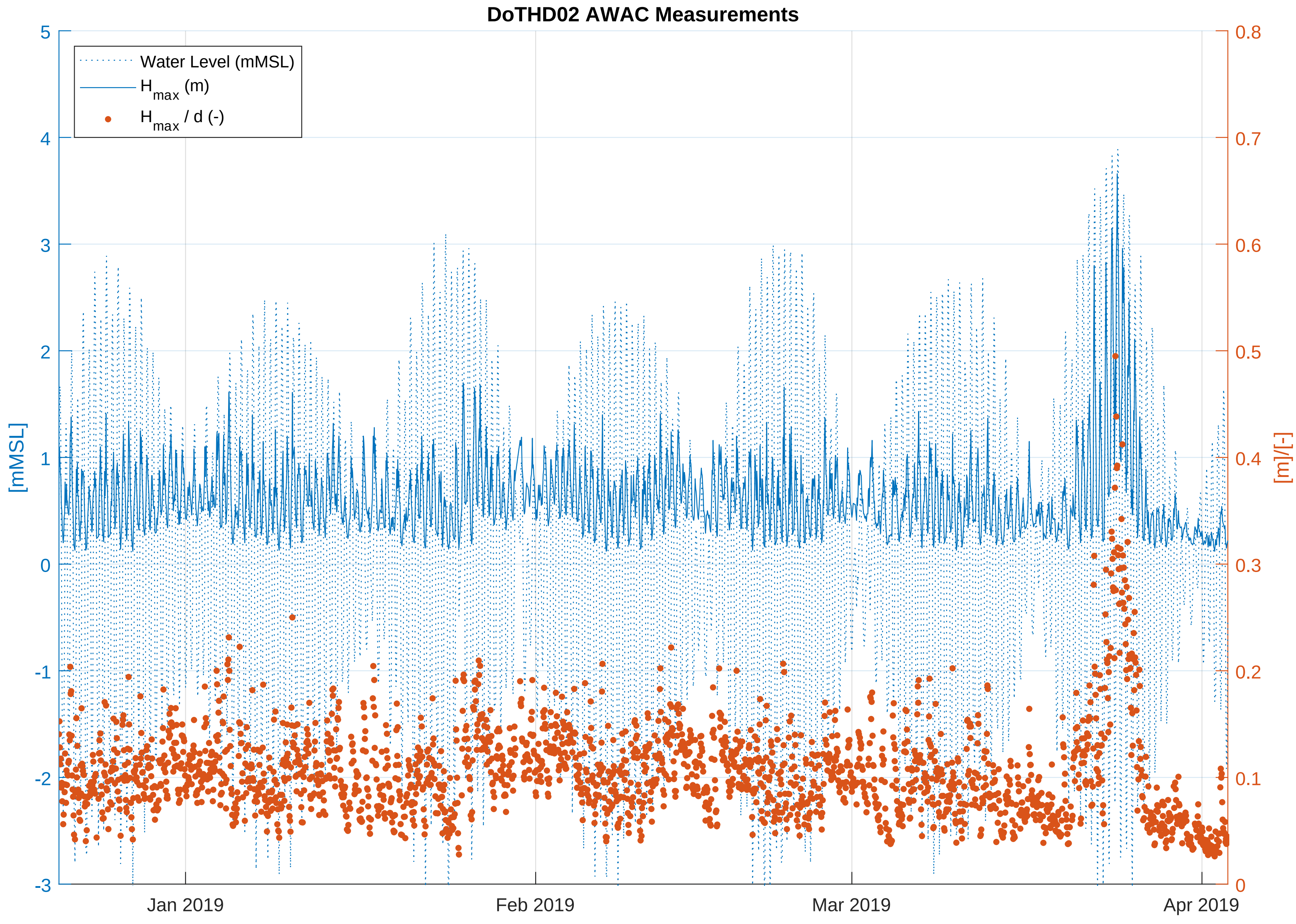


13143.101 | 26-Aug-2019
DoTHD01_HmaxD_Timeseries.fig

Baird.

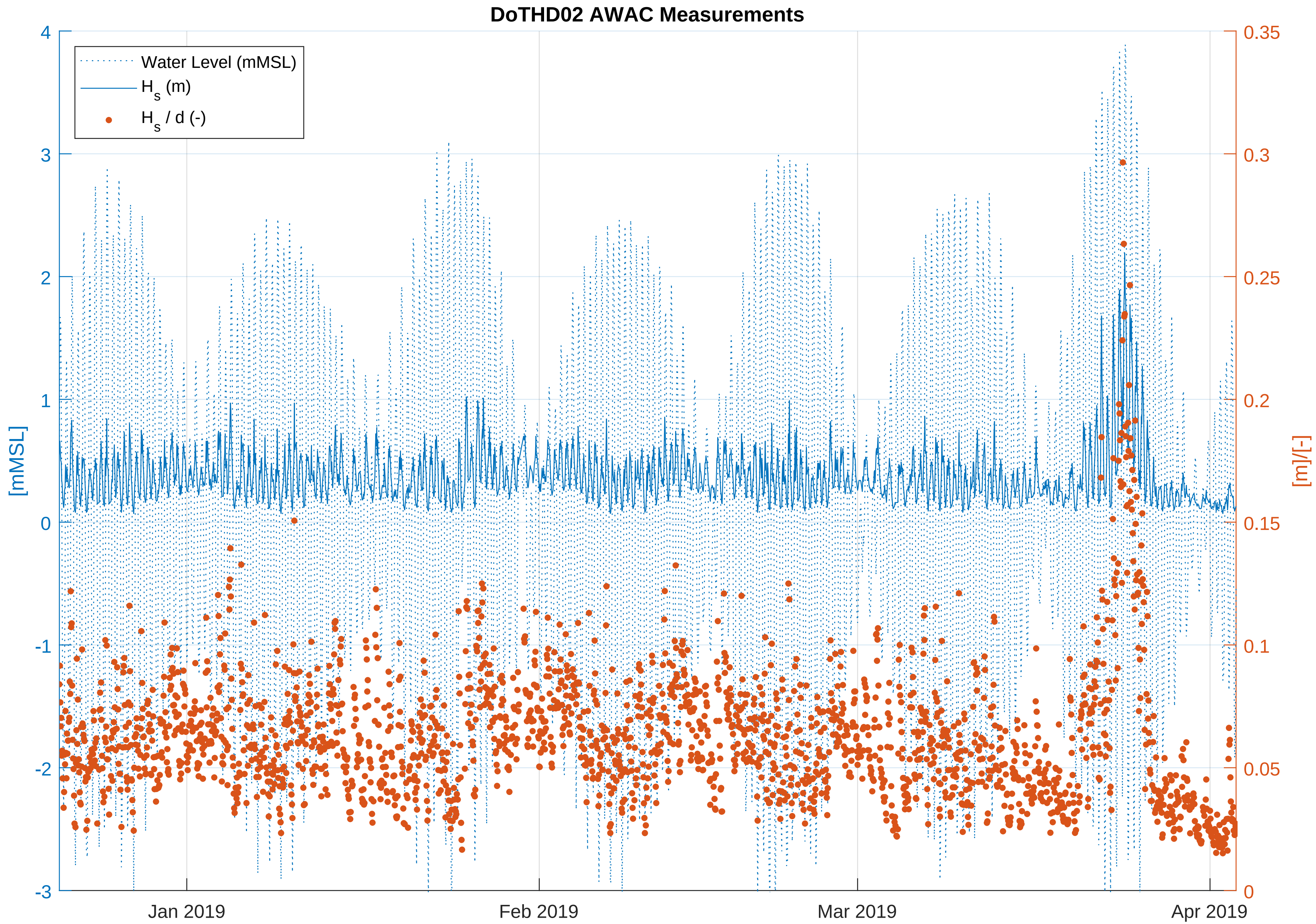


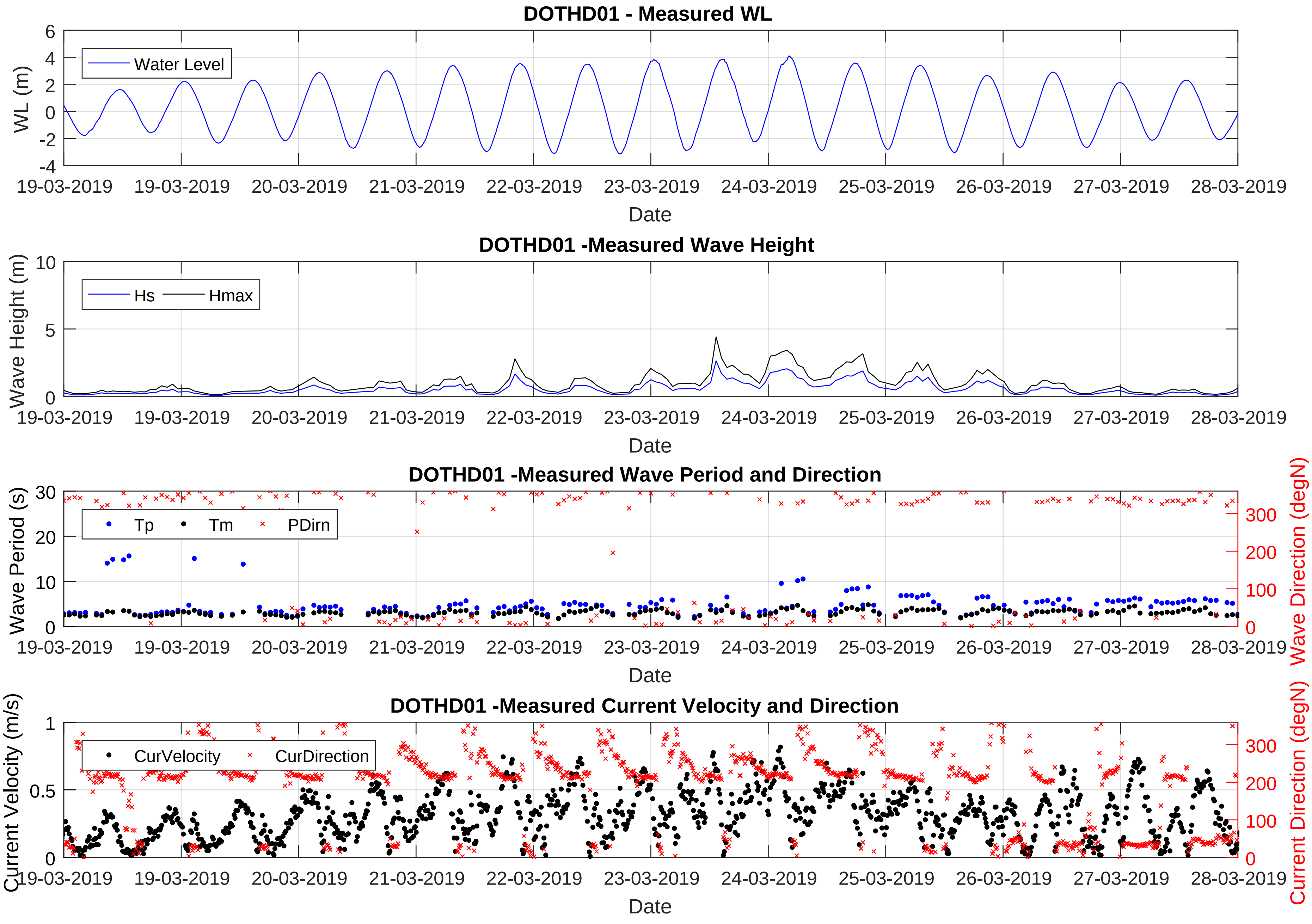
13143.101 | Aug-2019
DoTHD01_HsD_Timeseries.fig



13143.101 | Aug-2019
DoTHD02_HmaxD_Timeseries.fig

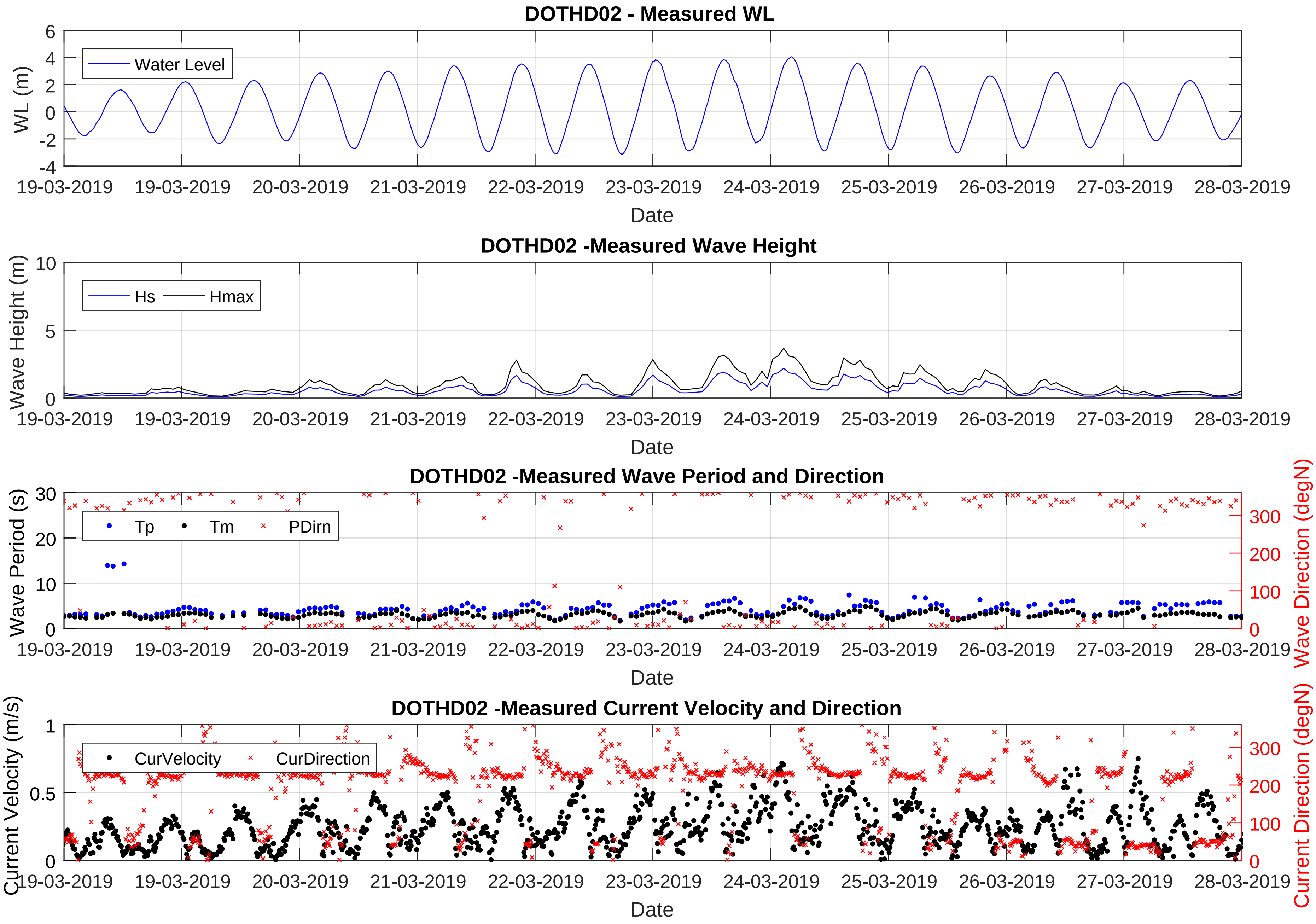
Baird.


DoTHD02 AWAC Measurements
Water Level (mMSL)
H_s (m)
H_s / d (-)
[mMSL]
[m]/[-]
4
3
2
1
0
-1
-2
-3
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Jan 2019
Feb 2019
Mar 2019
Apr 2019



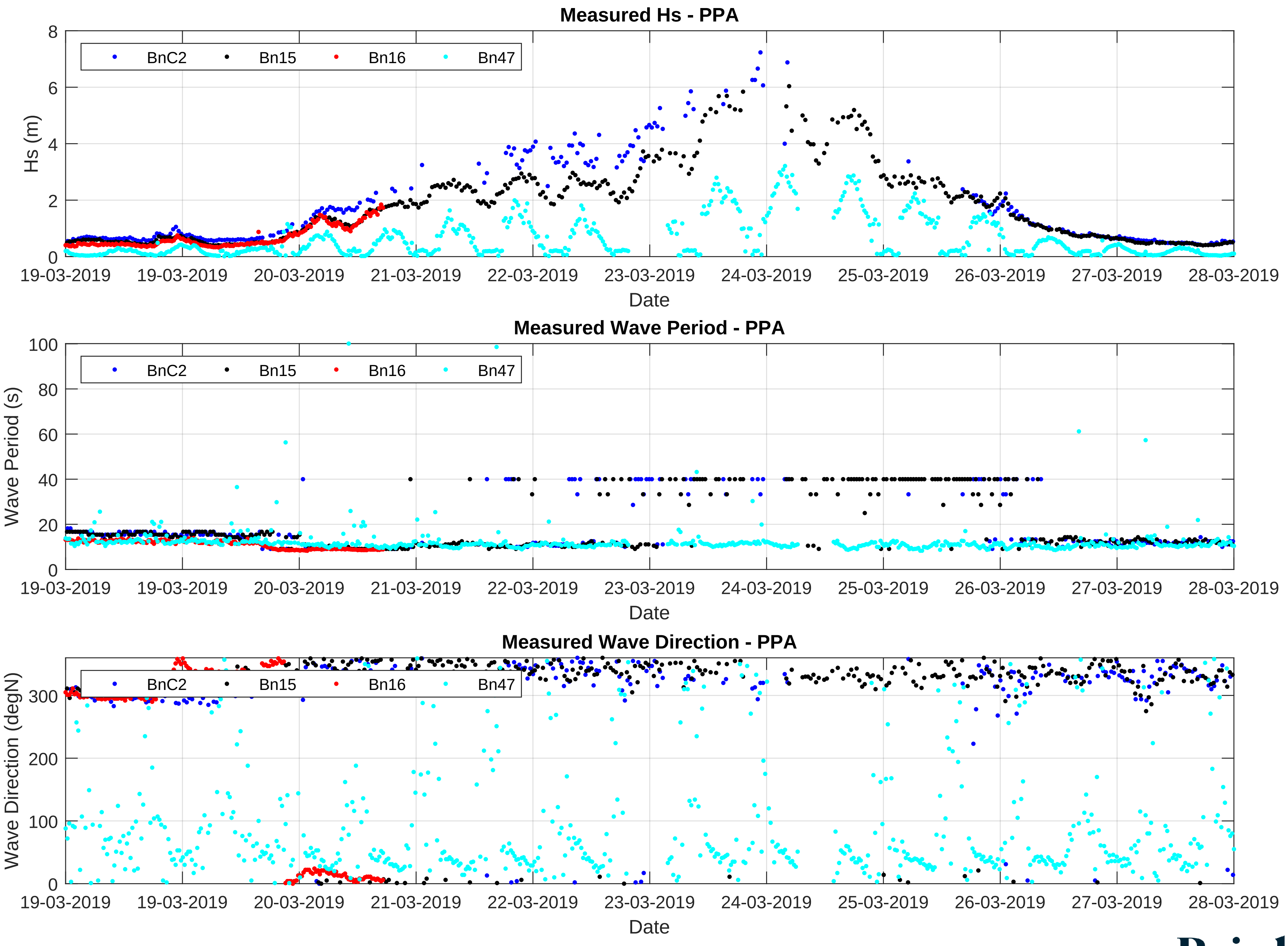
DOTHD01 - Measured WL
Water Level
WL (m)
Date
DOTHD01 -Measured Wave Height
Hs
Hmax
Wave Height (m)
Date
DOTHD01 -Measured Wave Period and Direction
Tp
Tm
PDirn
Wave Period (s)
Wave Direction (degN)
Date
DOTHD01 -Measured Current Velocity and Direction
CurVelocity
CurDirection
Current Velocity (m/s)
Current Direction (degN)
Date
19-03-2019
19-03-2019
20-03-2019
21-03-2019
22-03-2019
23-03-2019
24-03-2019
25-03-2019
26-03-2019
27-03-2019
28-03-2019

Baird.



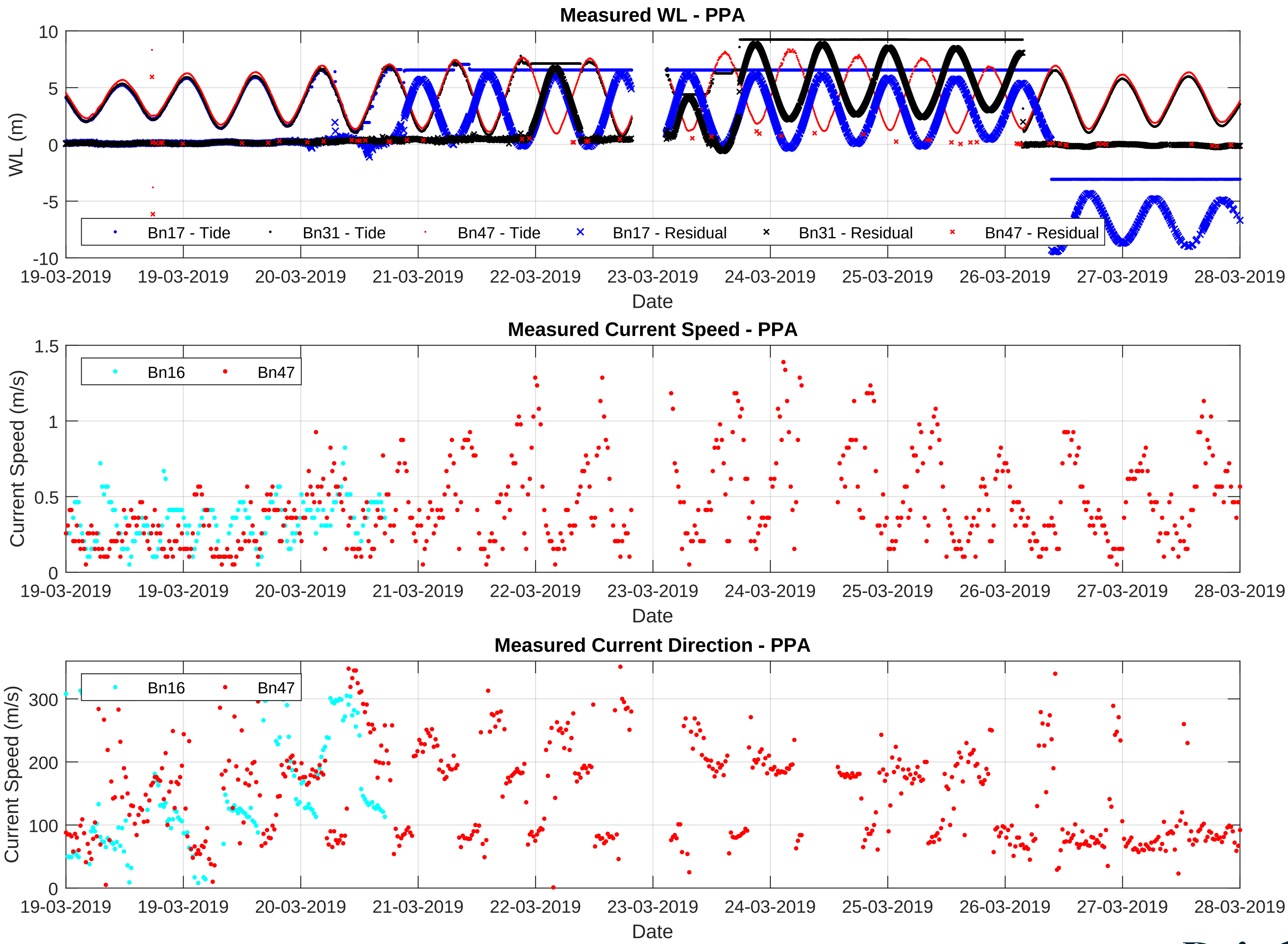
DOTHD02 - Measured WL
Water Level
WL (m)
Date
DOTHD02 -Measured Wave Height
Hs
Hmax
Wave Height (m)
Date
DOTHD02 -Measured Wave Period and Direction
Tp
Tm
PDirn
Wave Period (s)
Wave Direction (degN)
Date
DOTHD02 -Measured Current Velocity and Direction
CurVelocity
CurDirection
Current Velocity (m/s)
Current Direction (degN)
Date
19-03-2019
19-03-2019
20-03-2019
21-03-2019
22-03-2019
23-03-2019
24-03-2019
25-03-2019
26-03-2019
27-03-2019
28-03-2019

Baird.



Measured Hs - PPA
BnC2
Bn15
Bn16
Bn47
Hs (m)
0
2
4
6
8
Date
19-03-2019
19-03-2019
20-03-2019
21-03-2019
22-03-2019
23-03-2019
24-03-2019
25-03-2019
26-03-2019
27-03-2019
28-03-2019
Measured Wave Period - PPA
Wave Period (s)
0
20
40
60
80
100
Measured Wave Direction - PPA
Wave Direction (degN)
0
100
200
300

Baird.

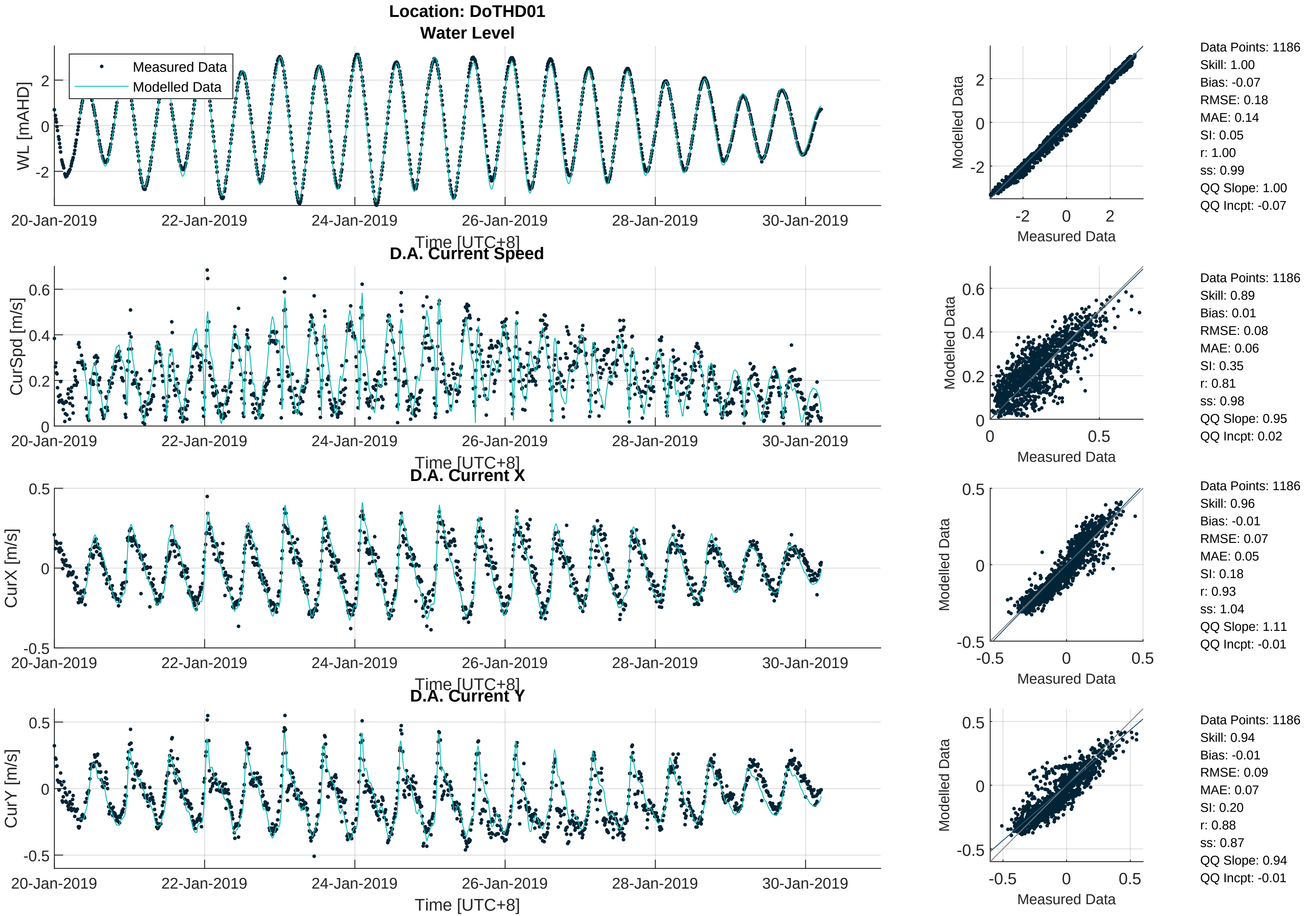


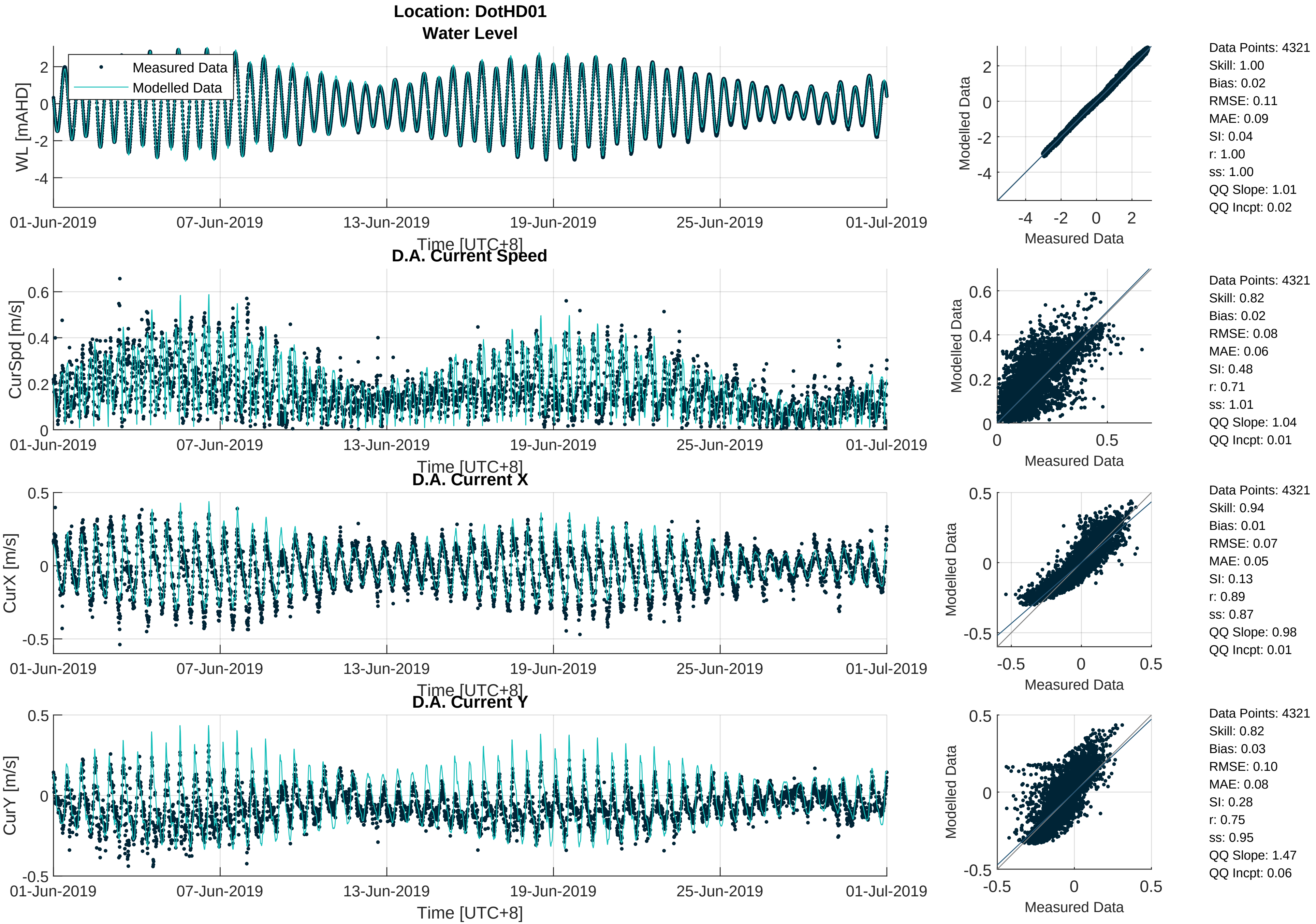
Baird.

13143.101 | 17-Jun-2019

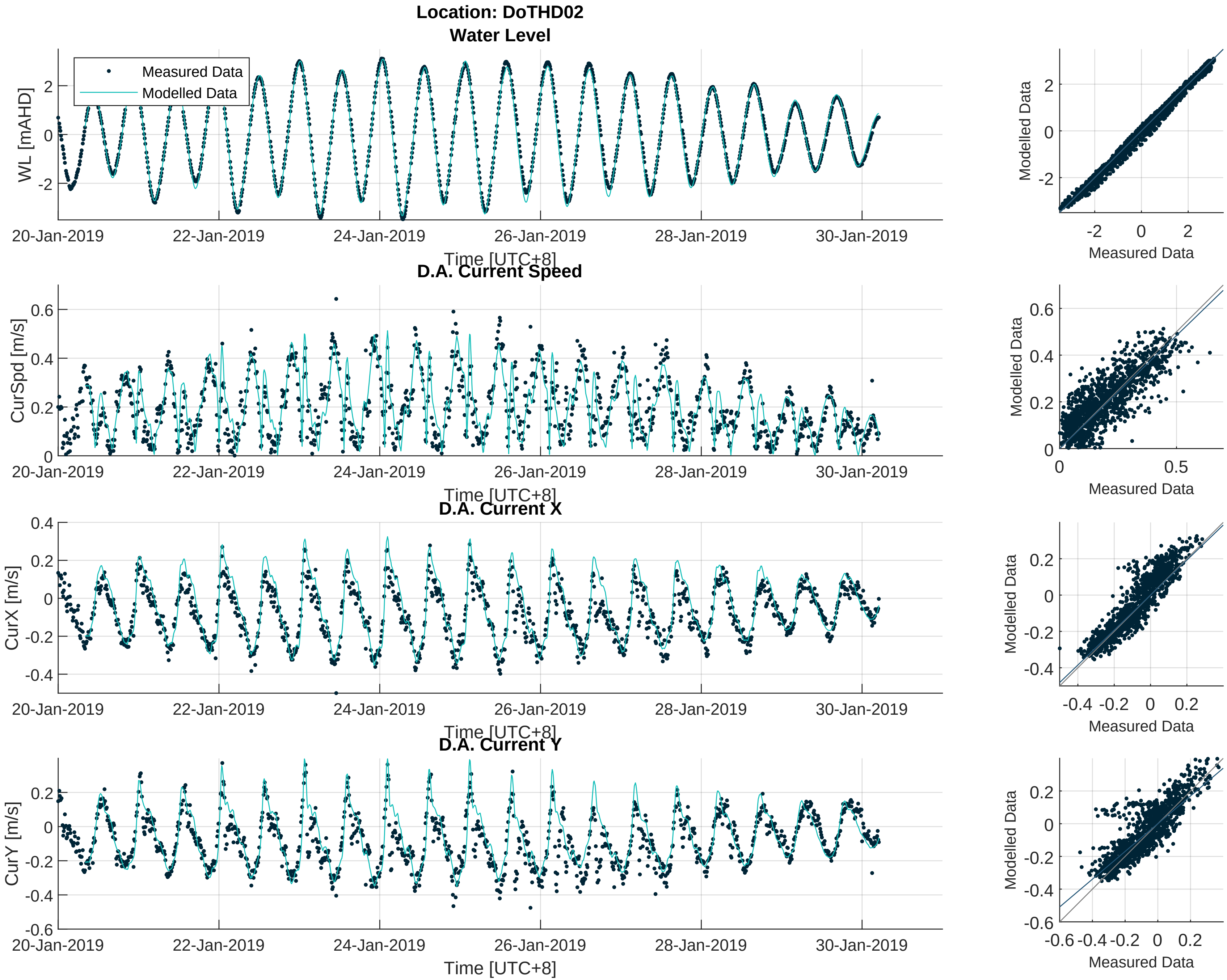
N:\13143.101_DoT_SpoilbankMarina\05_Analyses\MetoceanData\CompositePlots\PPA_TCVeronica_WL_Cur.pdf

B.1 Model Validation – Ambient Conditions


Location: DoTHD01
Water Level
Measured Data
Modelled Data
WL [mAHD]
Time [UTC+8]
D.A. Current Speed
CurSpd [m/s]
D.A. Current X
CurX [m/s]
D.A. Current Y
CurY [m/s]
20-Jan-2019
22-Jan-2019
24-Jan-2019
26-Jan-2019
28-Jan-2019
30-Jan-2019
Modelled Data
Measured Data
Data Points: 1186
Skill: 1.00
Bias: -0.07
RMSE: 0.18
MAE: 0.14
SI: 0.05
r: 1.00
ss: 0.99
QQ Slope: 1.00
QQ Incpt: -0.07
Data Points: 1186
Skill: 0.89
Bias: 0.01
RMSE: 0.08
MAE: 0.06
SI: 0.35
r: 0.81
ss: 0.98
QQ Slope: 0.95
QQ Incpt: 0.02
Data Points: 1186
Skill: 0.96
Bias: -0.01
RMSE: 0.07
MAE: 0.05
SI: 0.18
r: 0.93
ss: 1.04
QQ Slope: 1.11
QQ Incpt: -0.01
Data Points: 1186
Skill: 0.94
Bias: -0.01
RMSE: 0.09
MAE: 0.07
SI: 0.20
r: 0.88
ss: 0.87
QQ Slope: 0.94
QQ Incpt: -0.01



Location: DotHD01
Water Level
Measured Data
Modelled Data
WL [mAHD]
Time [UTC+8]
Modelled Data
Measured Data
Data Points: 4321
Skill: 1.00
Bias: 0.02
RMSE: 0.11
MAE: 0.09
SI: 0.04
r: 1.00
ss: 1.00
QQ Slope: 1.01
QQ Incpt: 0.02
D.A. Current Speed
CurSpd [m/s]
Time [UTC+8]
Data Points: 4321
Skill: 0.82
Bias: 0.02
RMSE: 0.08
MAE: 0.06
SI: 0.48
r: 0.71
ss: 1.01
QQ Slope: 1.04
QQ Incpt: 0.01
D.A. Current X
CurX [m/s]
Time [UTC+8]
Data Points: 4321
Skill: 0.94
Bias: 0.01
RMSE: 0.07
MAE: 0.05
SI: 0.13
r: 0.89
ss: 0.87
QQ Slope: 0.98
QQ Incpt: 0.01
D.A. Current Y
CurY [m/s]
Time [UTC+8]
Data Points: 4321
Skill: 0.82
Bias: 0.03
RMSE: 0.10
MAE: 0.08
SI: 0.28
r: 0.75
ss: 0.95
QQ Slope: 1.47
QQ Incpt: 0.06
01-Jun-2019
07-Jun-2019
13-Jun-2019
19-Jun-2019
25-Jun-2019
01-Jul-2019

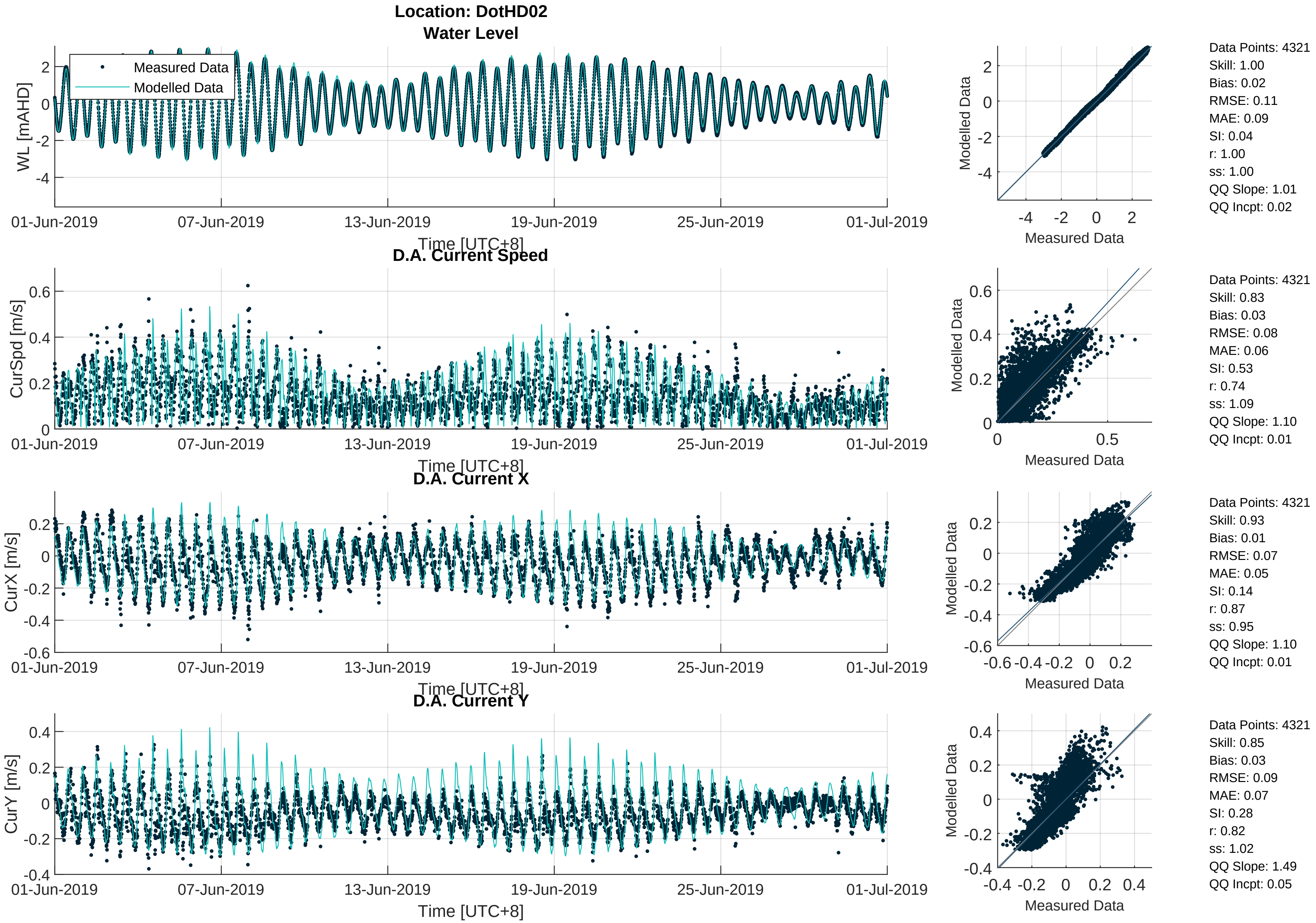


Data Points: 1186
Skill: 1.00
Bias: -0.06
RMSE: 0.18
MAE: 0.14
SI: 0.05
r: 1.00
ss: 1.00
QQ Slope: 1.01
QQ Incpt: -0.06

Data Points: 1186
Skill: 0.90
Bias: 0.01
RMSE: 0.07
MAE: 0.06
SI: 0.37
r: 0.82
ss: 0.97
QQ Slope: 0.92
QQ Incpt: 0.03

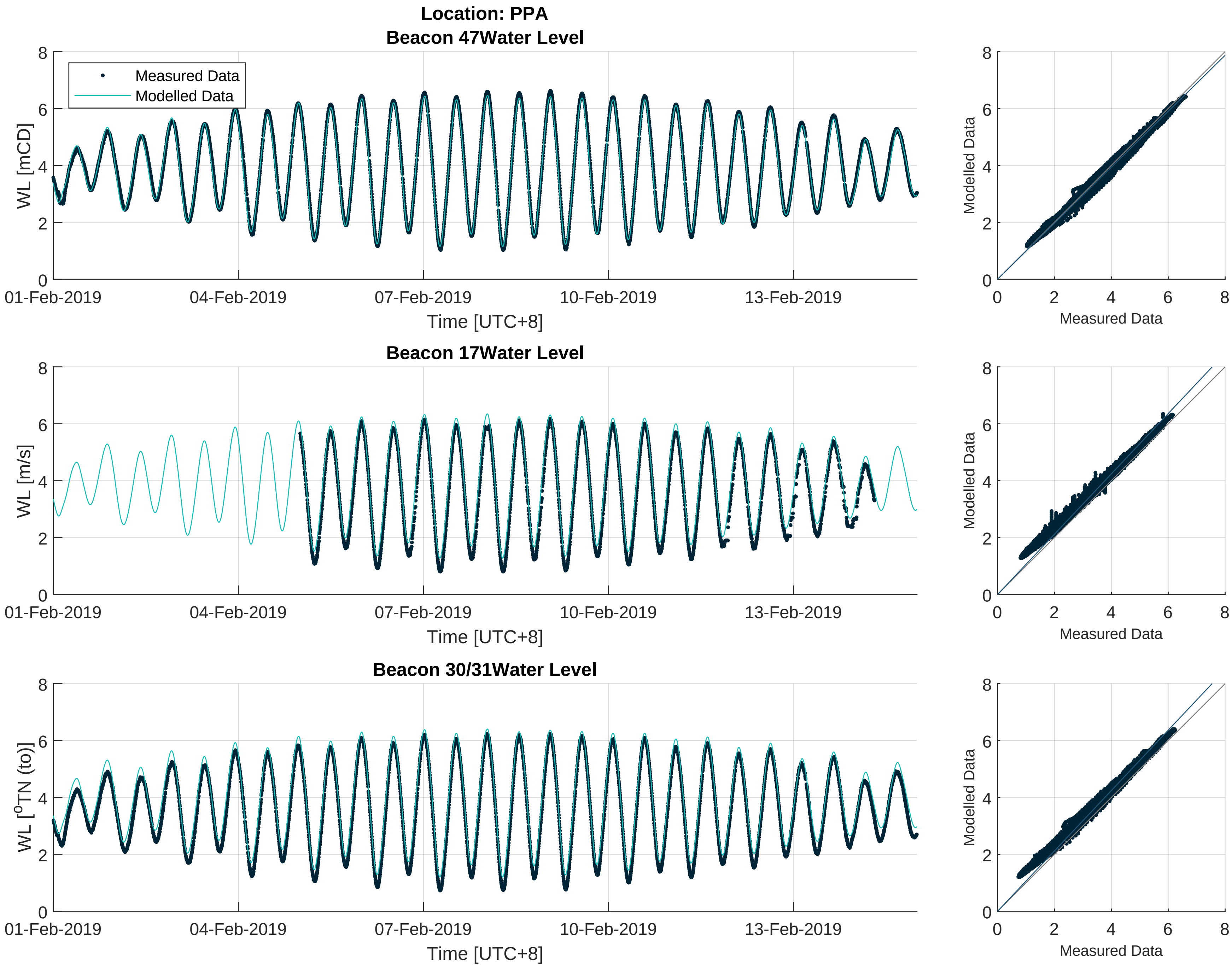
Data Points: 1186
Skill: 0.94
Bias: 0.03
RMSE: 0.07
MAE: 0.05
SI: 0.17
r: 0.92
ss: 0.96
QQ Slope: 1.17
QQ Incpt: 0.04

Data Points: 1186
Skill: 0.91
Bias: 0.02
RMSE: 0.09
MAE: 0.06
SI: 0.23
r: 0.85
ss: 0.85
QQ Slope: 1.05
QQ Incpt: 0.03



13143.101 | Nov-2019

N:\Projects\13143.101_DoT_SpoilbankMarina\10_Reports&Pres\01_Figures\figs\DotHD02-Measured-D3D-Modelled-DA-Winter\TS_plots\TS_plots_DotHD02-Measured-D3D-Modelled-DA-Winter.fig

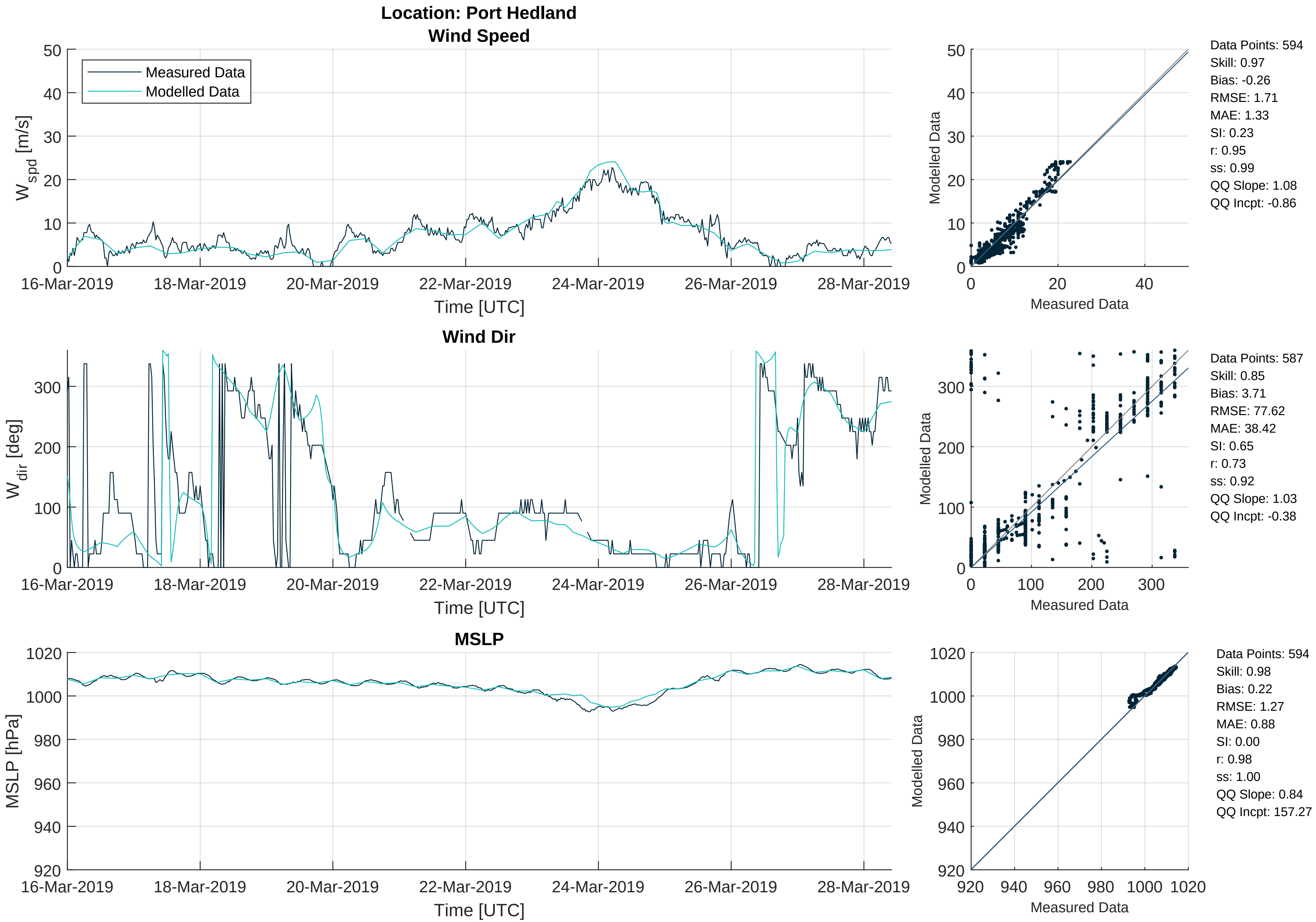


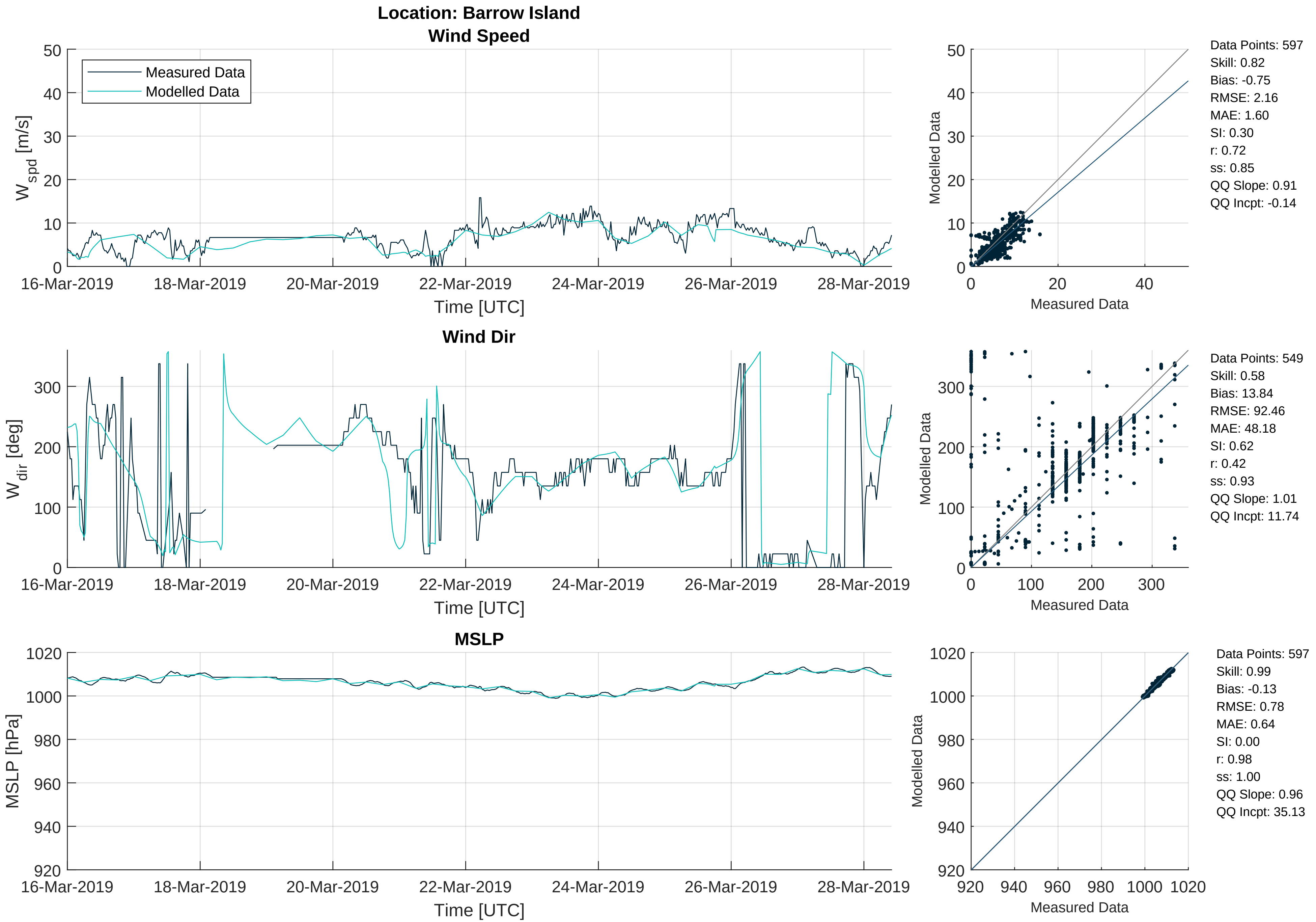
Data Points: 4030
Skill: 1.00
Bias: -0.06
RMSE: 0.15
MAE: 0.13
SI: 0.04
r: 1.00
ss: 0.98
QQ Slope: 0.97
QQ Incpt: 0.07

Data Points: 2679
Skill: 0.99
Bias: 0.29
RMSE: 0.33
MAE: 0.29
SI: 0.04
r: 1.00
ss: 1.06
QQ Slope: 0.95
QQ Incpt: 0.46

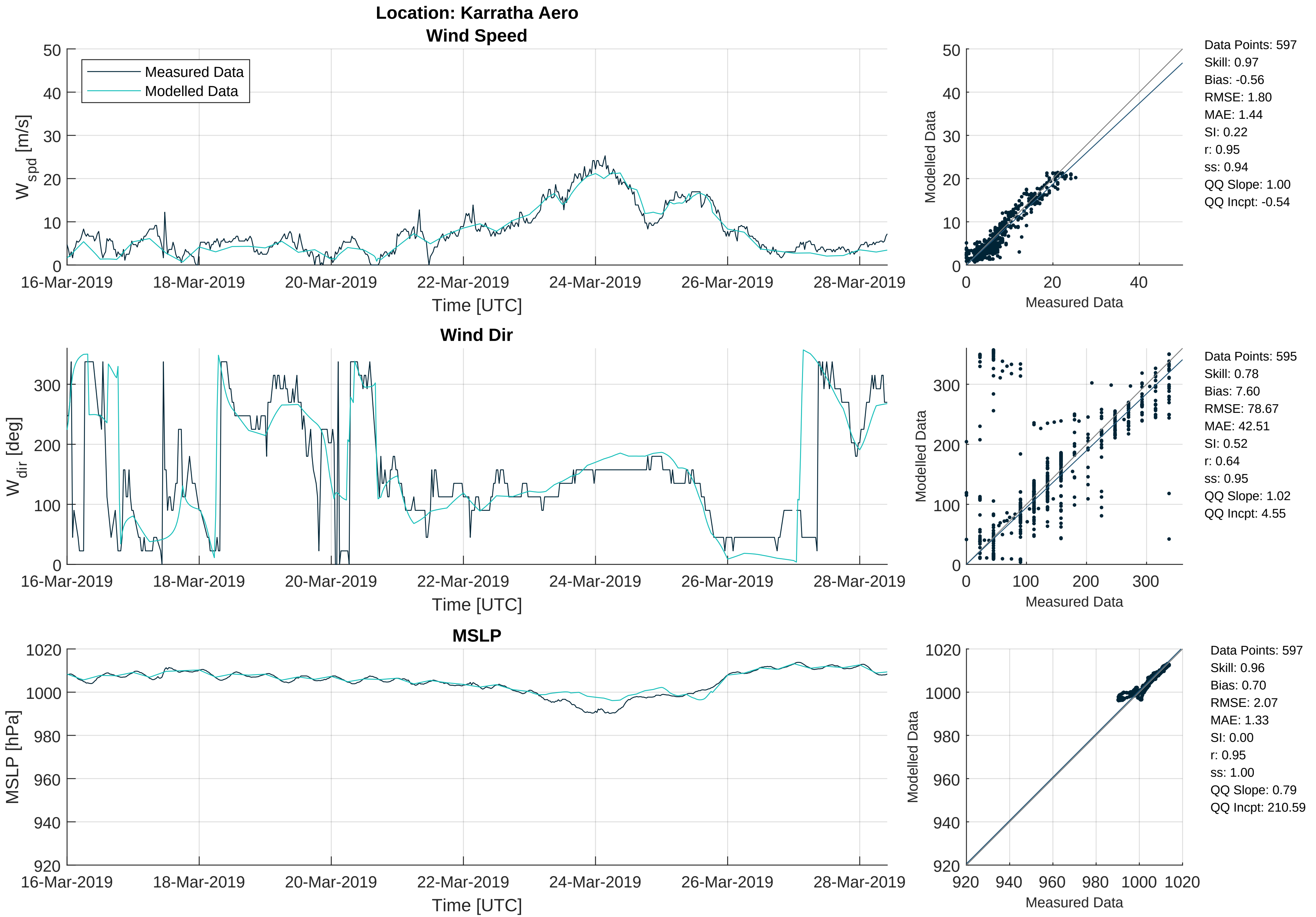
Data Points: 4028
Skill: 0.99
Bias: 0.28
RMSE: 0.31
MAE: 0.28
SI: 0.04
r: 1.00
ss: 1.06
QQ Slope: 0.96
QQ Incpt: 0.43

B.2 Model Validation – Cyclonic Conditions

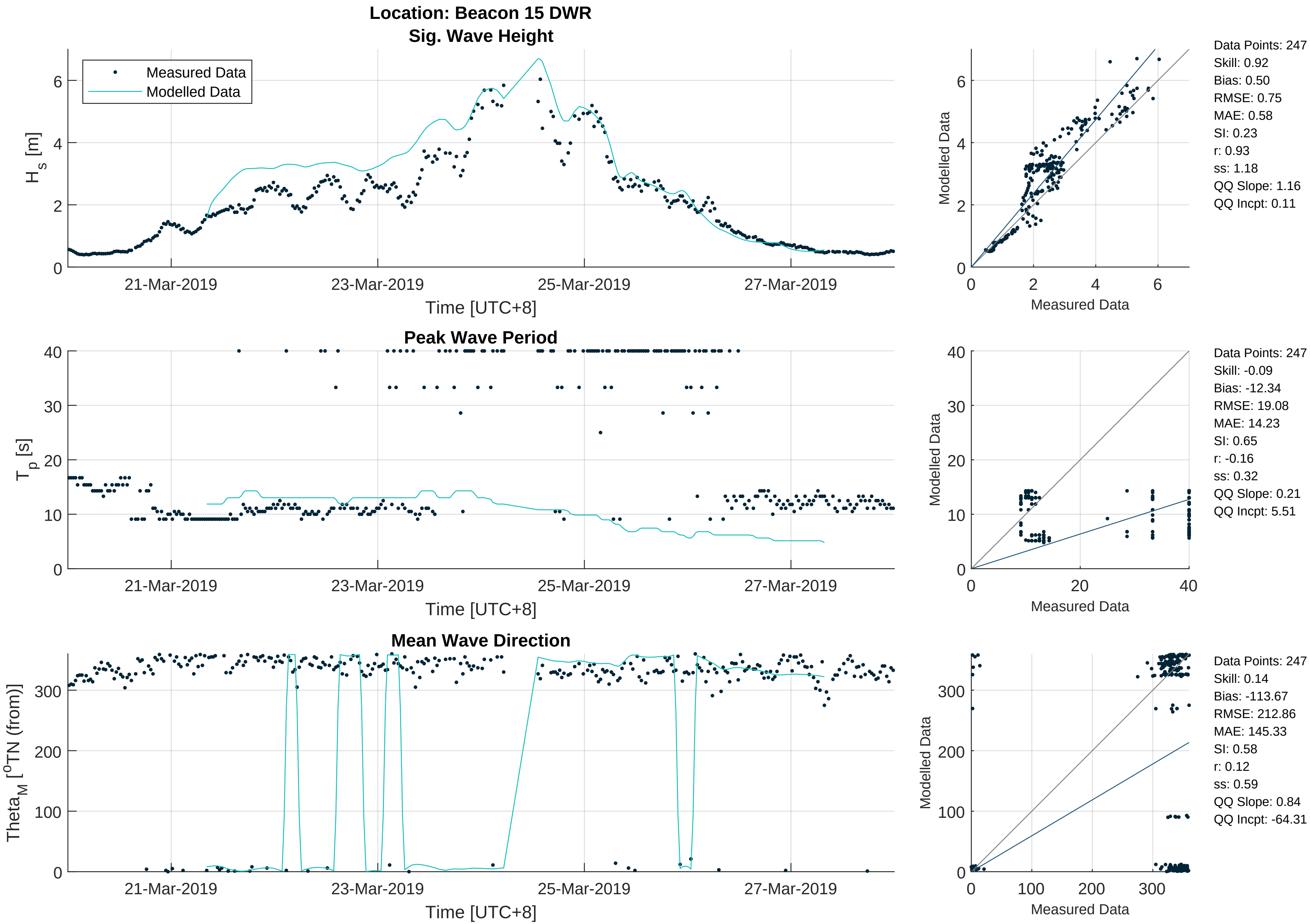

Location: Port Hedland
Wind Speed
Measured Data
Modelled Data
W spd [m/s]
Time [UTC]
16-Mar-2019
18-Mar-2019
20-Mar-2019
22-Mar-2019
24-Mar-2019
26-Mar-2019
28-Mar-2019
Modelled Data
Measured Data
Data Points: 594
Skill: 0.97
Bias: -0.26
RMSE: 1.71
MAE: 1.33
SI: 0.23
r: 0.95
ss: 0.99
QQ Slope: 1.08
QQ Incpt: -0.86
Wind Dir
W dir [deg]
Data Points: 587
Skill: 0.85
Bias: 3.71
RMSE: 77.62
MAE: 38.42
SI: 0.65
r: 0.73
ss: 0.92
QQ Slope: 1.03
QQ Incpt: -0.38
MSLP
MSLP [hPa]
Data Points: 594
Skill: 0.98
Bias: 0.22
RMSE: 1.27
MAE: 0.88
SI: 0.00
r: 0.98
ss: 1.00
QQ Slope: 0.84
QQ Incpt: 157.27



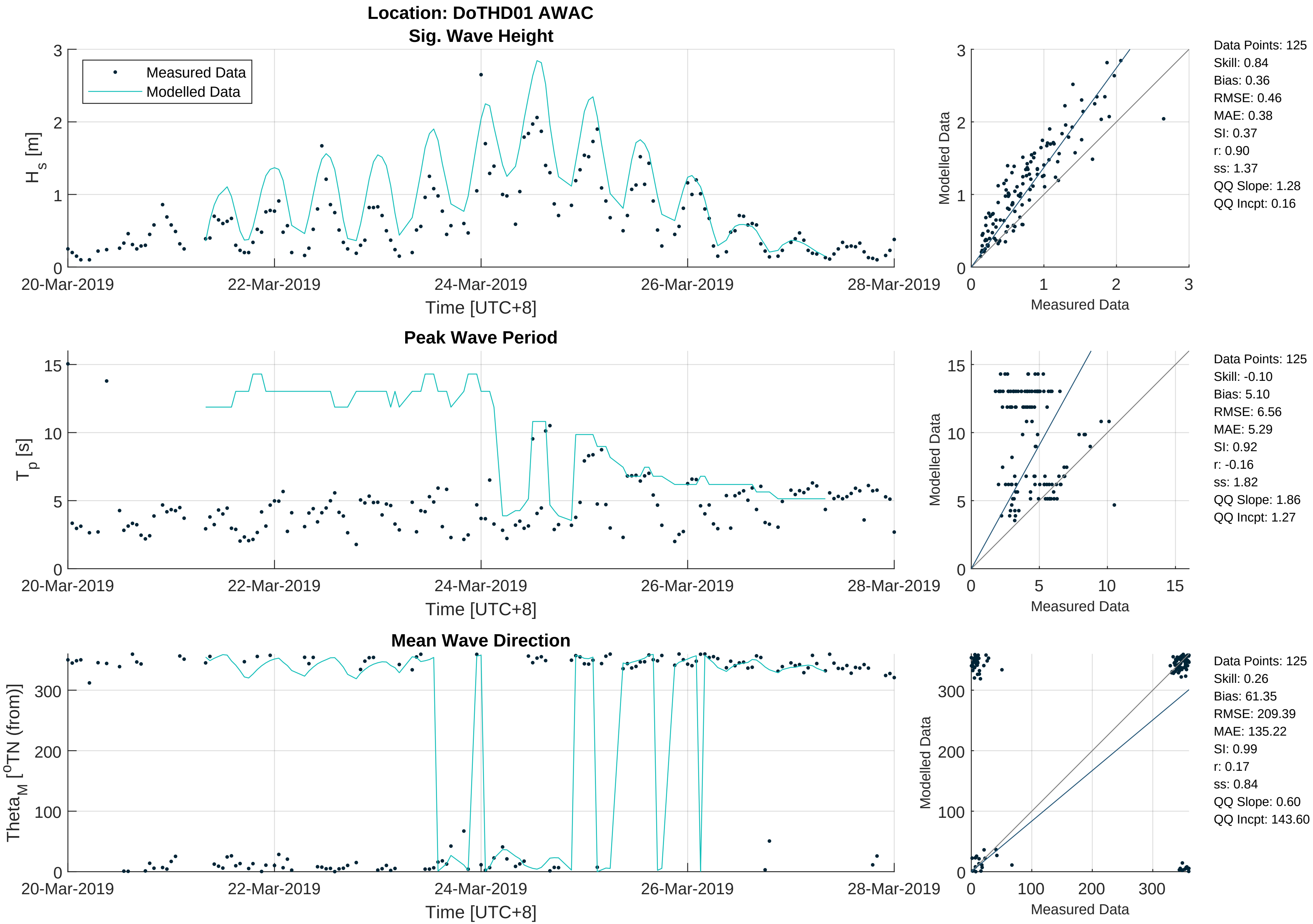
Location: Barrow Island
Wind Speed
Measured Data
Modelled Data
W spd [m/s]
Time [UTC]
16-Mar-2019
18-Mar-2019
20-Mar-2019
22-Mar-2019
24-Mar-2019
26-Mar-2019
28-Mar-2019
Modelled Data
Measured Data
Data Points: 597
Skill: 0.82
Bias: -0.75
RMSE: 2.16
MAE: 1.60
SI: 0.30
r: 0.72
ss: 0.85
QQ Slope: 0.91
QQ Incpt: -0.14
Wind Dir
W dir [deg]
Time [UTC]
Modelled Data
Measured Data
Data Points: 549
Skill: 0.58
Bias: 13.84
RMSE: 92.46
MAE: 48.18
SI: 0.62
r: 0.42
ss: 0.93
QQ Slope: 1.01
QQ Incpt: 11.74
MSLP
MSLP [hPa]
Time [UTC]
Modelled Data
Measured Data
Data Points: 597
Skill: 0.99
Bias: -0.13
RMSE: 0.78
MAE: 0.64
SI: 0.00
r: 0.98
ss: 1.00
QQ Slope: 0.96
QQ Incpt: 35.13



Location: Karratha Aero
Wind Speed
Measured Data
Modelled Data
W_{spd} [m/s]
Time [UTC]
16-Mar-2019
18-Mar-2019
20-Mar-2019
22-Mar-2019
24-Mar-2019
26-Mar-2019
28-Mar-2019
Modelled Data
Measured Data
Data Points: 597
Skill: 0.97
Bias: -0.56
RMSE: 1.80
MAE: 1.44
SI: 0.22
r: 0.95
ss: 0.94
QQ Slope: 1.00
QQ Incpt: -0.54
Wind Dir
W_{dir} [deg]
Time [UTC]
Modelled Data
Measured Data
Data Points: 595
Skill: 0.78
Bias: 7.60
RMSE: 78.67
MAE: 42.51
SI: 0.52
r: 0.64
ss: 0.95
QQ Slope: 1.02
QQ Incpt: 4.55
MSLP
MSLP [hPa]
Time [UTC]
Modelled Data
Measured Data
Data Points: 597
Skill: 0.96
Bias: 0.70
RMSE: 2.07
MAE: 1.33
SI: 0.00
r: 0.95
ss: 1.00
QQ Slope: 0.79
QQ Incpt: 210.59

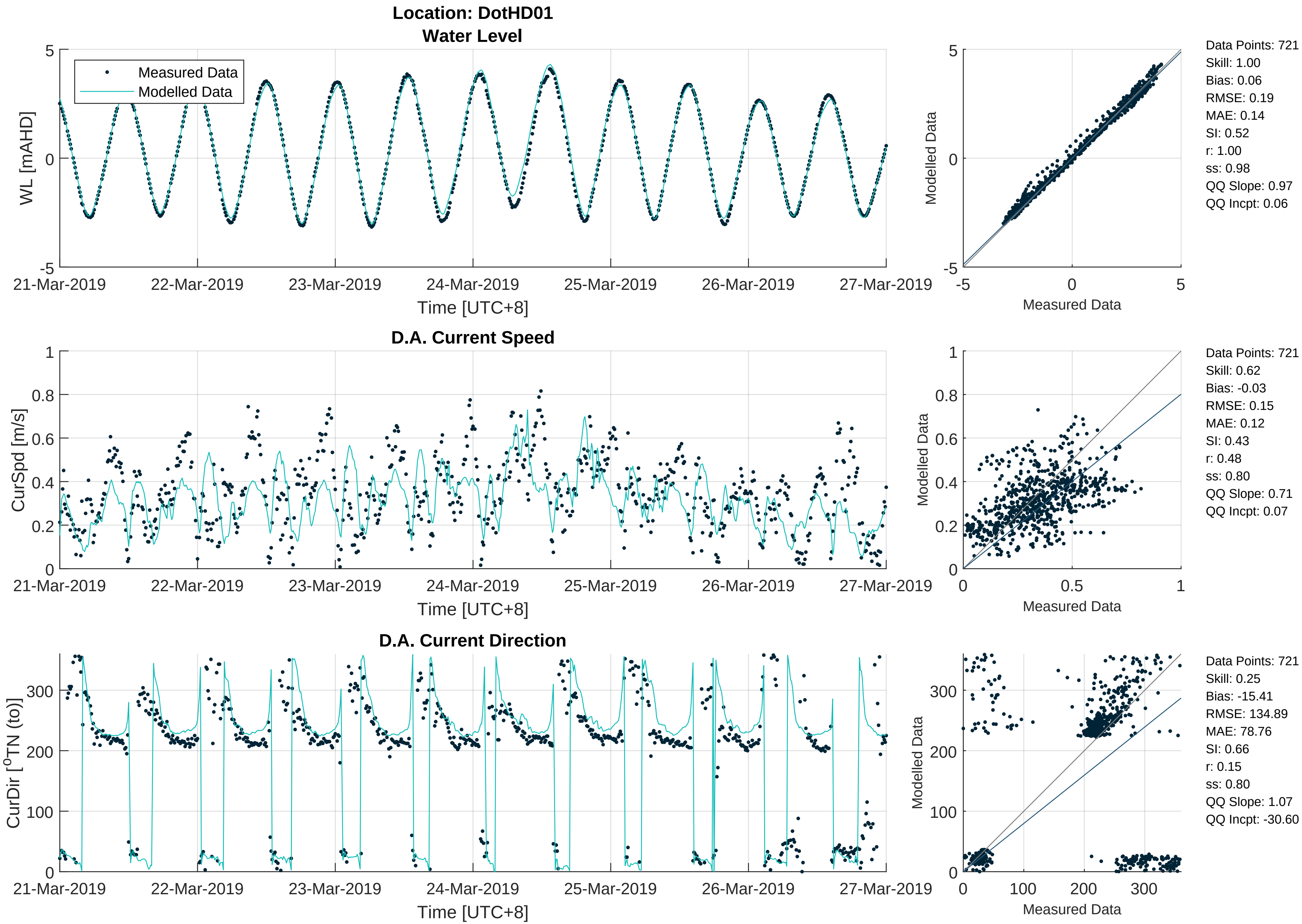


Location: Beacon 15 DWR
Sig. Wave Height
Measured Data
Modelled Data
H_s [m]
Time [UTC+8]
21-Mar-2019
23-Mar-2019
25-Mar-2019
27-Mar-2019
Modelled Data
Measured Data
Data Points: 247
Skill: 0.92
Bias: 0.50
RMSE: 0.75
MAE: 0.58
SI: 0.23
r: 0.93
ss: 1.18
QQ Slope: 1.16
QQ Incpt: 0.11
Peak Wave Period
T_p [s]
Data Points: 247
Skill: -0.09
Bias: -12.34
RMSE: 19.08
MAE: 14.23
SI: 0.65
r: -0.16
ss: 0.32
QQ Slope: 0.21
QQ Incpt: 5.51
Mean Wave Direction
Theta_M [°TN (from)]
Data Points: 247
Skill: 0.14
Bias: -113.67
RMSE: 212.86
MAE: 145.33
SI: 0.58
r: 0.12
ss: 0.59
QQ Slope: 0.84
QQ Incpt: -64.31

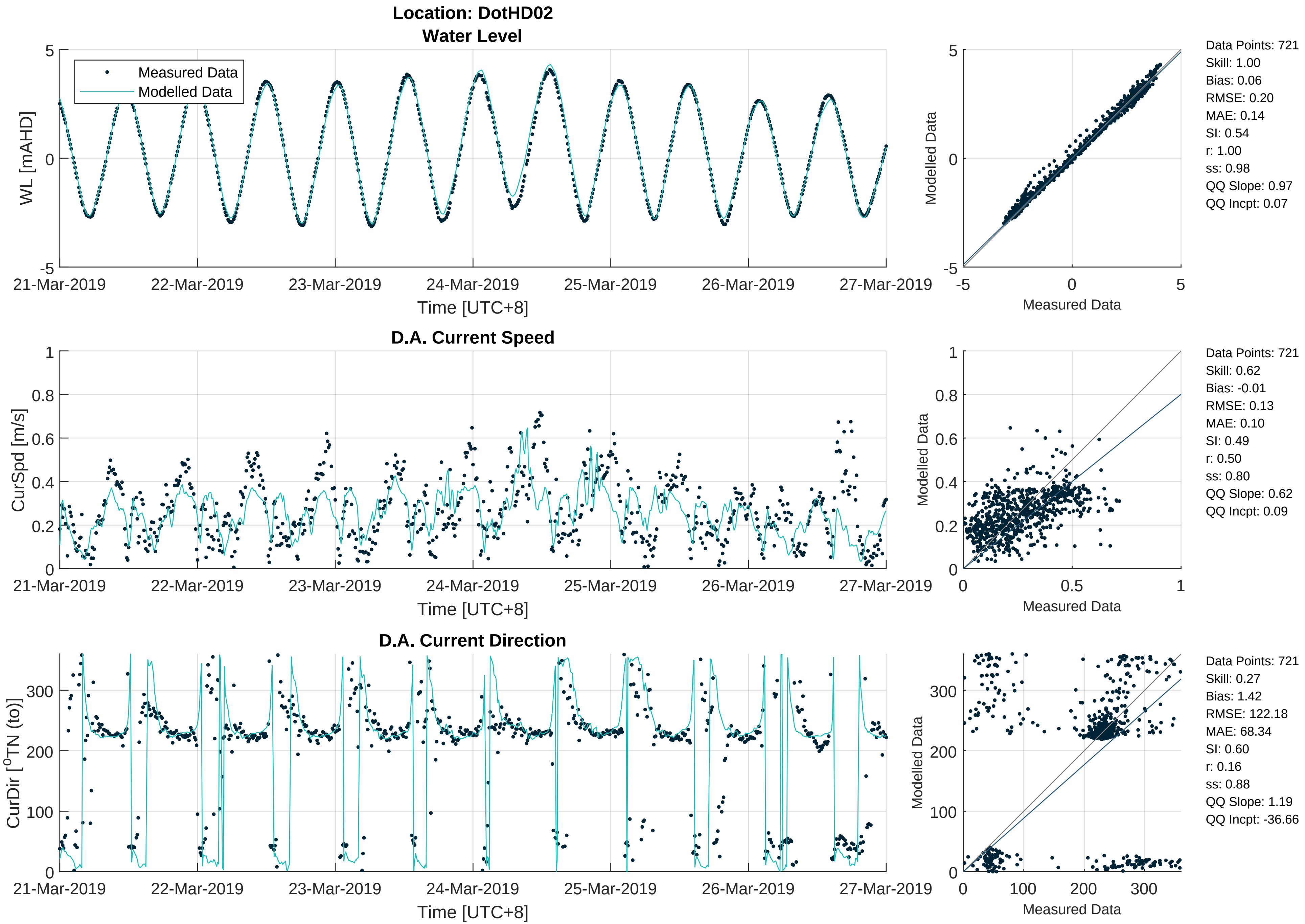


Location: DoTHD01 AWAC
Sig. Wave Height
Measured Data
Modelled Data
H_s [m]
Time [UTC+8]
20-Mar-2019
22-Mar-2019
24-Mar-2019
26-Mar-2019
28-Mar-2019
Modelled Data
Measured Data
Data Points: 125
Skill: 0.84
Bias: 0.36
RMSE: 0.46
MAE: 0.38
SI: 0.37
r: 0.90
ss: 1.37
QQ Slope: 1.28
QQ Incpt: 0.16
Peak Wave Period
T_p [s]
Data Points: 125
Skill: -0.10
Bias: 5.10
RMSE: 6.56
MAE: 5.29
SI: 0.92
r: -0.16
ss: 1.82
QQ Slope: 1.86
QQ Incpt: 1.27
Mean Wave Direction
Theta_M [°TN (from)]
Data Points: 125
Skill: 0.26
Bias: 61.35
RMSE: 209.39
MAE: 135.22
SI: 0.99
r: 0.17
ss: 0.84
QQ Slope: 0.60
QQ Incpt: 143.60

Baird.



Location: DotHD01
Water Level
Measured Data
Modelled Data
WL [mAHD]
Time [UTC+8]
21-Mar-2019
22-Mar-2019
23-Mar-2019
24-Mar-2019
25-Mar-2019
26-Mar-2019
27-Mar-2019
Modelled Data
Measured Data
Data Points: 721
Skill: 1.00
Bias: 0.06
RMSE: 0.19
MAE: 0.14
SI: 0.52
r: 1.00
ss: 0.98
QQ Slope: 0.97
QQ Incpt: 0.06
D.A. Current Speed
CurSpd [m/s]
Time [UTC+8]
Modelled Data
Measured Data
Data Points: 721
Skill: 0.62
Bias: -0.03
RMSE: 0.15
MAE: 0.12
SI: 0.43
r: 0.48
ss: 0.80
QQ Slope: 0.71
QQ Incpt: 0.07
D.A. Current Direction
CurDir [^{o}TN (to)]
Time [UTC+8]
Modelled Data
Measured Data
Data Points: 721
Skill: 0.25
Bias: -15.41
RMSE: 134.89
MAE: 78.76
SI: 0.66
r: 0.15
ss: 0.80
QQ Slope: 1.07
QQ Incpt: -30.60


Location: DotHD02
Water Level
Measured Data
Modelled Data
WL [mAHD]
Time [UTC+8]
Modelled Data
Measured Data
Data Points: 721
Skill: 1.00
Bias: 0.06
RMSE: 0.20
MAE: 0.14
SI: 0.54
r: 1.00
ss: 0.98
QQ Slope: 0.97
QQ Incpt: 0.07
D.A. Current Speed
CurSpd [m/s]
Time [UTC+8]
Modelled Data
Measured Data
Data Points: 721
Skill: 0.62
Bias: -0.01
RMSE: 0.13
MAE: 0.10
SI: 0.49
r: 0.50
ss: 0.80
QQ Slope: 0.62
QQ Incpt: 0.09
D.A. Current Direction
CurDir [^{o}TN (to)]
Time [UTC+8]
Modelled Data
Measured Data
Data Points: 721
Skill: 0.27
Bias: 1.42
RMSE: 122.18
MAE: 68.34
SI: 0.60
r: 0.16
ss: 0.88
QQ Slope: 1.19
QQ Incpt: -36.66
21-Mar-2019
22-Mar-2019
23-Mar-2019
24-Mar-2019
25-Mar-2019
26-Mar-2019
27-Mar-2019

Appendix C

Metocean Design Criteria

C.1 Spatial Metocean Design Criteria

Metocean design criteria is presented spatially across the marina development for 12 metocean zones defined in Figure C.1. Design parameters for winds, water levels, waves and currents are presented for existing climate conditions and for water levels and waves under a sea level rise condition of +0.39m (50-year planning period).

Recurrence intervals of 1, 5, 20, 100 and 500-years ARI are presented in Tables C.1 to C.5 respectively.

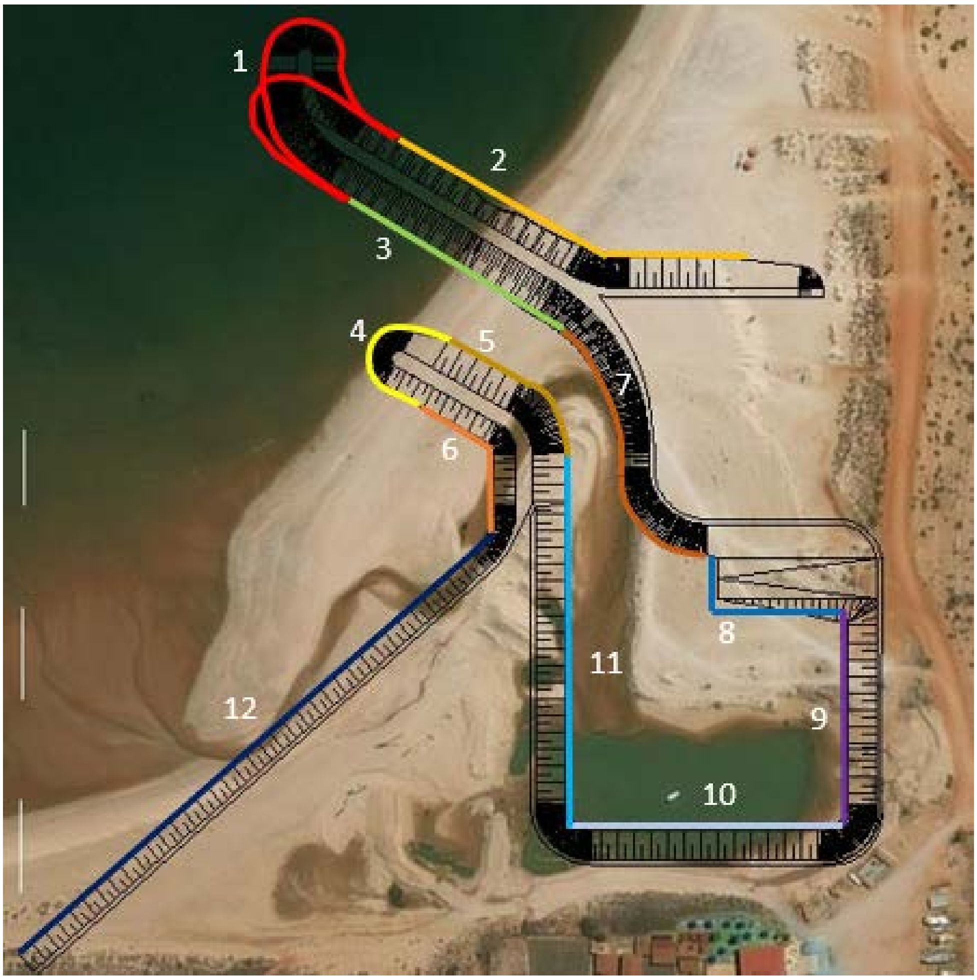


Figure C.1: Definition of Metocean Zone for Spatial Metocean Design Criteria

Table 7.1: 1-year ARI Metocean Design Criteria for all Metocean Zones

		Metocean Zones											
Parameter	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Winds													
10-minute Mean Overwater Wind Speed at 10mAMSL	m/s	27.3	27.3	27.3	27.3	27.3	27.3	27.3	27.3	27.3	27.3	27.3	27.3
Water Levels													
Peak Total Still Water Level (excl Wave Setup)	mCD	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Peak Total Still Water Level (incl Wave Setup)	mCD	7.2	7.4	7.2	7.2	7.2	7.4	7.2	7.2	7.2	7.2	7.2	7.4
Seastate													
Significant Wave Height (Hs)	m	1.90	1.45	0.65	1.30	0.60	0.50	0.45	0.10*	0.10*	0.10*	0.10*	1.00
Peak Wave Period (Tp)	s	6 - 7.5	6 - 7.5	6 - 7.5	6 - 7.5	6 - 7.5	6 - 7.5	6 - 7.5	2 - 3	2 - 3	2 - 3	2 - 3	6 - 7.5
Zero Crossing Wave Period (Tz)	s	5.4	5.4	5.4	5.4	5.4	5.4	5.4	2.1	2.1	2.1	2.1	5.4
98th percentile Wave Height ($H_{2\%}$)	m	2.96	2.26	1.01	2.03	0.94	0.78	0.70	0.16	0.16	0.16	0.16	1.56
Maximum Wave Height (Hmax)	m	3.2	2.5	1.1	2.2	1.0	0.6	0.8	0.2	0.2	0.2	0.2	1.7
associated mean Wave Period for Hmax (Thmax)	s	6.8	6.8	6.8	6.8	6.8	6.8	6.8	2.7	2.7	2.7	2.7	6.8
Current													
Depth Averaged Currents	m/s	-	-	-	-	-	-	-	-	-	-	-	-
Sea Level Rise (50 year Planning Period)													
Peak Total Still Water Level (excl Wave Setup)	mCD	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
Peak Total Still Water Level (incl Wave Setup)	mCD	7.6	7.8	7.6	7.6	7.6	7.8	7.6	7.6	7.6	7.6	7.6	7.8
Significant Wave Height (Hs)	m	2.20	1.70	0.80	1.55	0.70	0.60	0.55	0.10*	0.10*	0.10*	0.10*	1.20

* Zones 8, 9, 10 & 11 (marina basin perimeter). Wave condition based on wind generated condition over basin fetch. Offshore wave penetration of Hs = 0.07m (at Tp = 6-7.5s) also possible.

Table 7.2: 5-year ARI Metocean Design Criteria for all Metocean Zones

		Metocean Zones											
Parameter	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Winds													
10-minute Mean Overwater Wind Speed at 10mAMSL	m/s	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5
Water Levels													
Peak Total Still Water Level (excl Wave Setup)	mCD	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
Peak Total Still Water Level (incl Wave Setup)	mCD	7.6	7.9	7.6	7.6	7.6	7.9	7.6	7.6	7.6	7.6	7.6	7.9
Seastate													
Significant Wave Height (Hs)	m	2.30	1.75	0.75	1.55	0.70	0.60	0.50	0.15*	0.15*	0.15*	0.15*	1.25
Peak Wave Period (Tp)	s	6 – 8	6 - 8	6 - 8	6 - 8	6 - 8	6 - 8	6 - 8	2 - 3	2 – 3	2 - 3	2 - 3	6 - 8
Zero Crossing Wave Period (Tz)	s	5.7	5.7	5.7	5.7	5.7	5.7	5.7	2.1	2.1	2.1	2.1	5.7
98th percentile Wave Height ($H_{2\%}$)	m	3.59	2.73	1.17	2.42	1.09	0.94	0.78	0.23	0.23	0.23	0.23	1.95
Maximum Wave Height (Hmax)	m	3.9	3.0	1.3	2.6	1.2	0.8	0.9	0.3	0.3	0.3	0.3	2.1
associated mean Wave Period for Hmax (Thmax)	s	7.3	7.3	7.3	7.3	7.3	7.3	7.3	2.7	2.7	2.7	2.7	7.3
Current													
Depth Averaged Currents	m/s	-	-	-	-	-	-	-	-	-	-	-	-
Sea Level Rise (50 year Planning Period)													
Peak Total Still Water Level (excl Wave Setup)	mCD	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Peak Total Still Water Level (incl Wave Setup)	mCD	8.0	8.3	8.0	8.0	8.0	8.3	8.0	8.0	8.0	8.0	8.0	8.3
Significant Wave Height (Hs)	m	2.60	2.00	0.85	1.80	0.80	0.70	0.60	0.15*	0.15*	0.15*	0.15*	1.45

* Zones 8, 9, 10 & 11 (marina basin perimeter). Wave condition based on wind generated condition over basin fetch. Offshore wave penetration of Hs = 0.08m (at Tp = 6.5-8s) also possible.

Table 7.3: 20-year ARI Metocean Design Criteria for all Metocean Zones

		Metocean Zones											
Parameter	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Winds													
10-minute Mean Overwater Wind Speed at 10mAMSL	m/s	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9
Water Levels													
Peak Total Still Water Level (excl Wave Setup)	mCD	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9
Peak Total Still Water Level (incl Wave Setup)	mCD	7.9	8.2	7.9	7.9	7.9	8.2	7.9	7.9	7.9	7.9	7.9	8.2
Seastate													
Significant Wave Height (Hs)	m	2.70	2.05	0.90	1.80	0.85	0.75	0.60	0.20*	0.20*	0.20*	0.20*	1.50
Peak Wave Period (Tp)	s	6 - 8.5	6 - 8.5	6 - 8.5	6 - 8.5	6 - 8.5	6 - 8.5	6 - 8.5	2 - 3	2 – 3	2 - 3	2 - 3	6 - 8.5
Zero Crossing Wave Period (Tz)	s	6.1	6.1	6.1	6.1	6.1	6.1	6.1	2.5	2.5	2.5	2.5	6.1
98th percentile Wave Height ($H_{2\%}$)	m	4.21	3.20	1.40	2.81	1.33	1.17	0.94	0.31	0.31	0.31	0.31	2.34
Maximum Wave Height (Hmax)	m	4.6	3.5	1.5	3.1	1.4	1.0	1.0	0.3	0.3	0.3	0.3	2.6
associated mean Wave Period for Hmax (Thmax)	s	7.7	7.7	7.7	7.7	7.7	7.7	7.7	3.2	3.2	3.2	3.2	7.7
Current													
Depth Averaged Currents	m/s	1.1	0.8	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.7
Sea Level Rise (50 year Planning Period)													
Peak Total Still Water Level (excl Wave Setup)	mCD	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Peak Total Still Water Level (incl Wave Setup)	mCD	8.3	8.6	8.3	8.3	8.3	8.6	8.3	8.3	8.3	8.3	8.3	8.6
Significant Wave Height (Hs)	m	2.95	2.25	1.00	2.00	0.95	0.85	0.65	0.20*	0.20*	0.20*	0.20*	1.65

* Zones 8, 9, 10 & 11 (marina basin perimeter). Wave condition based on wind generated condition over basin fetch. Offshore wave penetration of Hs=0.12m (at Tp = 7-8.5s) also possible.

Table 7.4: 100-year ARI Metocean Design Criteria for all Metocean Zones

		Metocean Zones											
Parameter	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Winds													
10-minute Mean Overwater Wind Speed at 10mAMSL	m/s	42.1	42.1	42.1	42.1	42.1	42.1	42.1	42.1	42.1	42.1	42.1	42.1
Water Levels													
Peak Total Still Water Level (excl Wave Setup)	mCD	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6
Peak Total Still Water Level (incl Wave Setup)	mCD	8.6	9	8.6	8.6	8.6	9	8.6	8.6	8.6	8.6	8.6	9
Seastate													
Significant Wave Height (Hs)	m	3.05	2.70	1.10	2.20	1.05	1.00	0.75	0.25*	0.25*	0.25*	0.25*	1.90
Peak Wave Period (Tp)	s	6 - 9.5	6 - 9.5	6 - 9.5	6 - 9.5	6 - 9.5	6 - 9.5	6 - 9.5	2 - 3	2 - 3	2 - 3	2 – 3	6 - 9.5
Zero Crossing Wave Period (Tz)	s	6.8	6.8	6.8	6.8	6.8	6.8	6.8	2.5	2.5	2.5	2.5	6.8
98th percentile Wave Height (H2%)	m	4.76	4.21	1.72	3.43	1.64	1.56	1.17	0.39	0.39	0.39	0.39	2.96
Maximum Wave Height (Hmax)	m	5.0	4.2	1.9	3.7	1.8	1.4	1.3	0.4	0.4	0.4	0.4	3.2
associated mean Wave Period for Hmax (Thmax)	s	8.6	8.6	8.6	8.6	8.6	8.6	8.6	3.2	3.2	3.2	3.2	8.6
Current													
Depth Averaged Currents	m/s	1.45	1.1	0.4	0.25	0.2	0.25	0.2	0.2	0.2	0.2	0.2	0.7
Sea Level Rise (50 year Planning Period)													
Peak Total Still Water Level (excl Wave Setup)	mCD	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Peak Total Still Water Level (incl Wave Setup)	mCD	9.0	9.3	9.0	9.0	9.0	9.3	9.0	9.0	9.0	9.0	9.0	9.3
Significant Wave Height (Hs)	m	3.20	2.85	1.15	2.30	1.10	1.05	0.80	0.25*	0.25*	0.25*	0.25*	2.00

* Zones 8, 9, 10 & 11 (marina basin perimeter). Wave condition based on wind generated condition over basin fetch. Offshore wave penetration of Hs=0.17m (at Tp = 8-9.5s) also possible

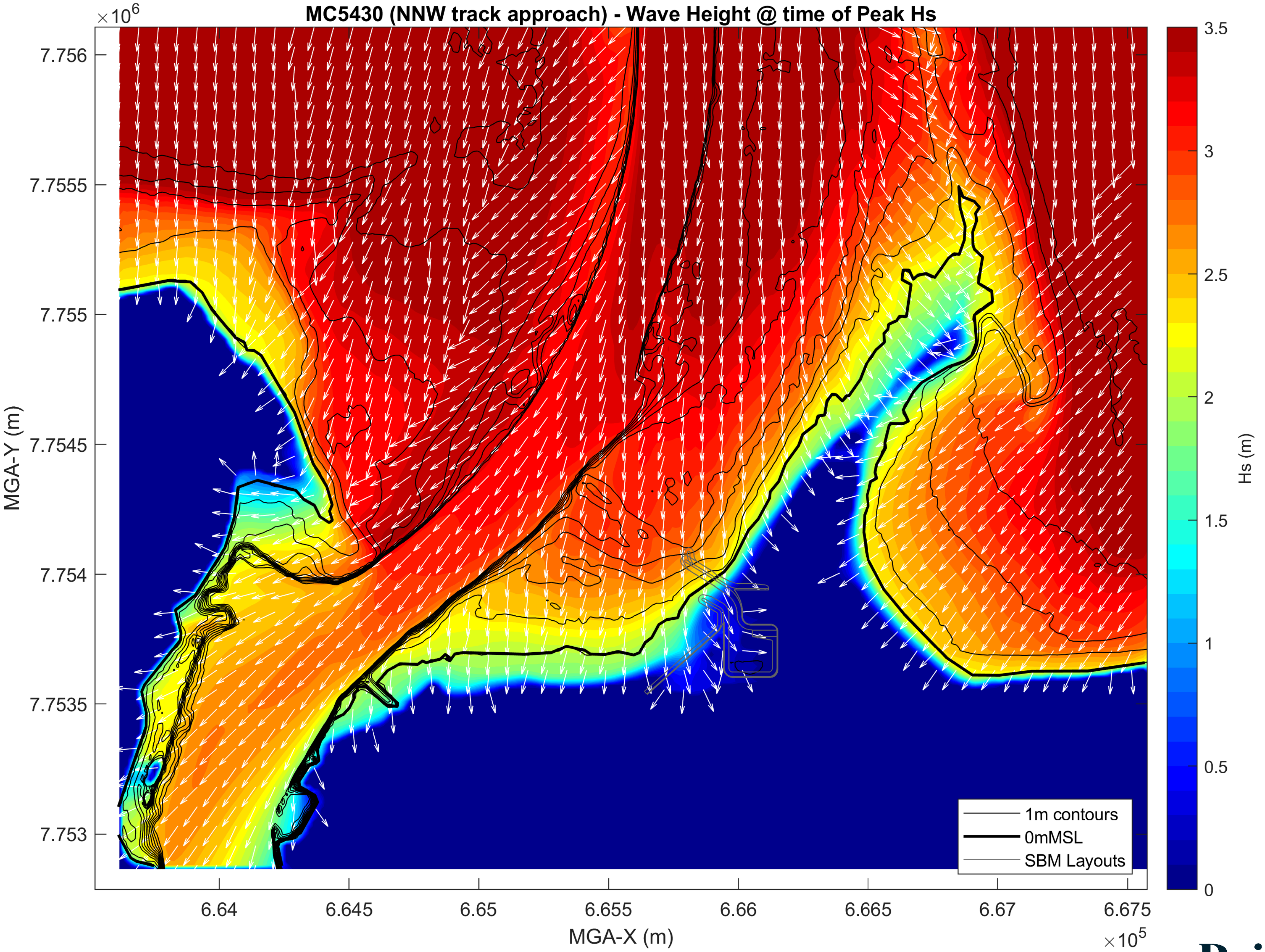
Table 7.5: 500-year ARI Metocean Design Criteria for all Metocean Zones

		Metocean Zones											
Parameter	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Winds													
10-minute Mean Overwater Wind Speed at 10mAMSL	m/s	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5
Water Levels													
Peak Total Still Water Level (excl Wave Setup)	mCD	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Peak Total Still Water Level (incl Wave Setup)	mCD	9.1	9.6	9.1	9.1	9.1	9.6	9.1	9.1	9.1	9.1	9.1	9.6
Seastate													
Significant Wave Height (Hs)	m	3.35	3.00	1.25	2.45	1.20	1.15	0.80	0.30*	0.30*	0.30*	0.37	2.15
Peak Wave Period (Tp)	s	6 - 10	6 - 10	6 - 10	6 - 10	6 - 10	6 - 10	6 - 10	2 - 3	2 – 3	2 - 3	8.5 - 10	6 - 10
Zero Crossing Wave Period (Tz)	s	7.1	7.1	7.1	7.1	7.1	7.1	7.1	2.9	2.9	2.9	7.1	7.1
98th percentile Wave Height (H2%)	m	5.23	4.68	1.95	3.82	1.87	1.79	1.25	0.47	0.47	0.47	0.58	3.35
Maximum Wave Height (Hmax)	m	5.7	4.5	2.1	4.2	2.0	1.8	1.4	0.5	0.5	0.5	0.6	3.7
associated mean Wave Period for Hmax (Thmax)	s	9.1	9.1	9.1	9.1	9.1	9.1	9.1	3.2	3.2	3.2	9.1	9.1
Current													
Depth Averaged Currents	m/s	1.65	1.3	0.55	0.35	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.9
Sea Level Rise (50 year Planning Period)													
Peak Total Still Water Level (excl Wave Setup)	mCD	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Peak Total Still Water Level (incl Wave Setup)	mCD	9.5	9.9	9.5	9.5	9.5	9.9	9.5	9.5	9.5	9.5	9.5	9.9
Significant Wave Height (Hs)	m	3.55	3.15	1.35	2.6	1.25	1.2	0.85	0.30*	0.30*	0.30*	0.4	2.25

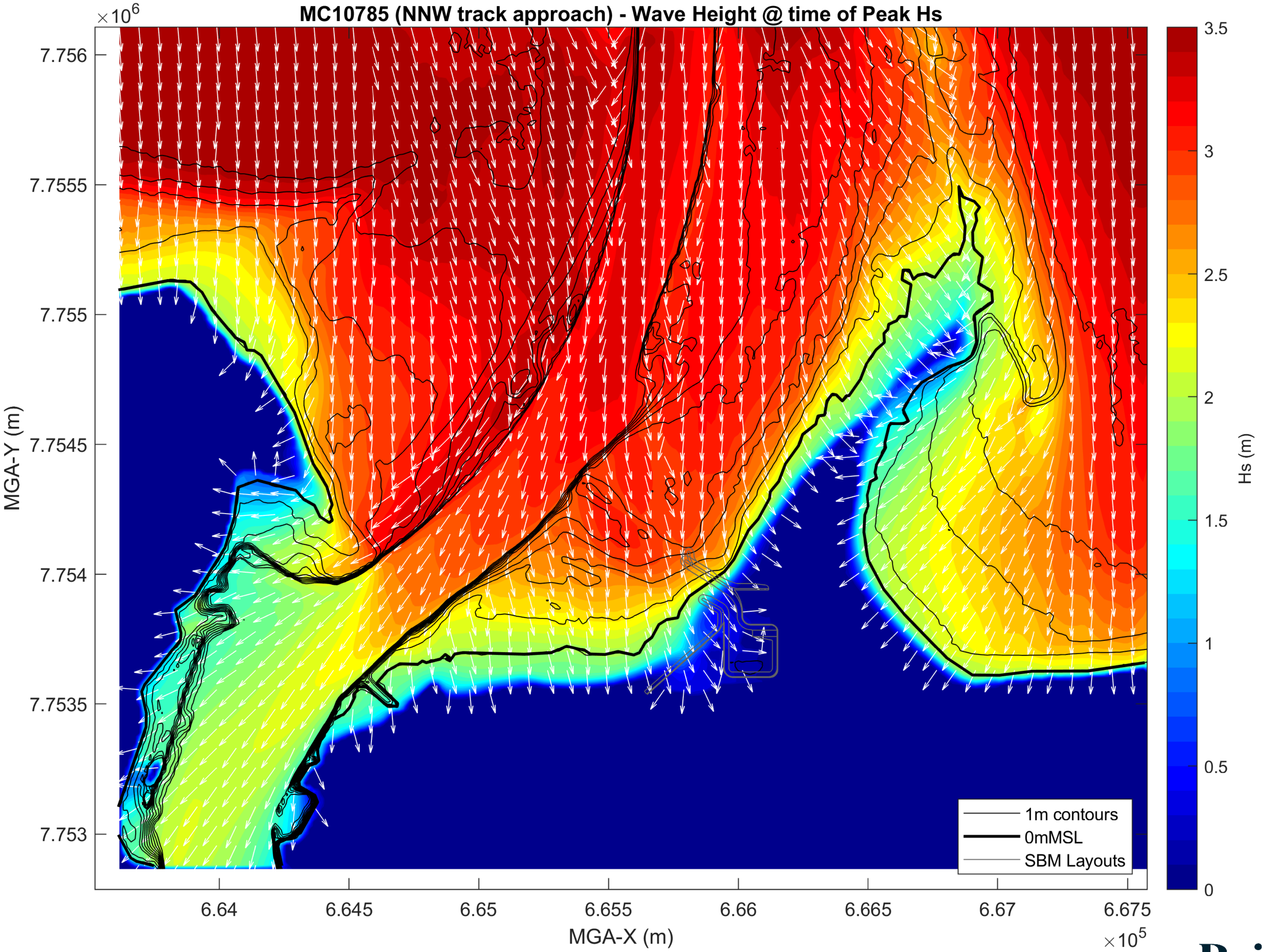
* Zones 8, 9, 10 & 11 (marina basin perimeter). Wave condition based on wind generated condition over basin fetch. Offshore wave penetration of Hs=0.20m (at Tp = 8.5-10s) also possible

Appendix D

100-year ARI Event Set Wave Maps

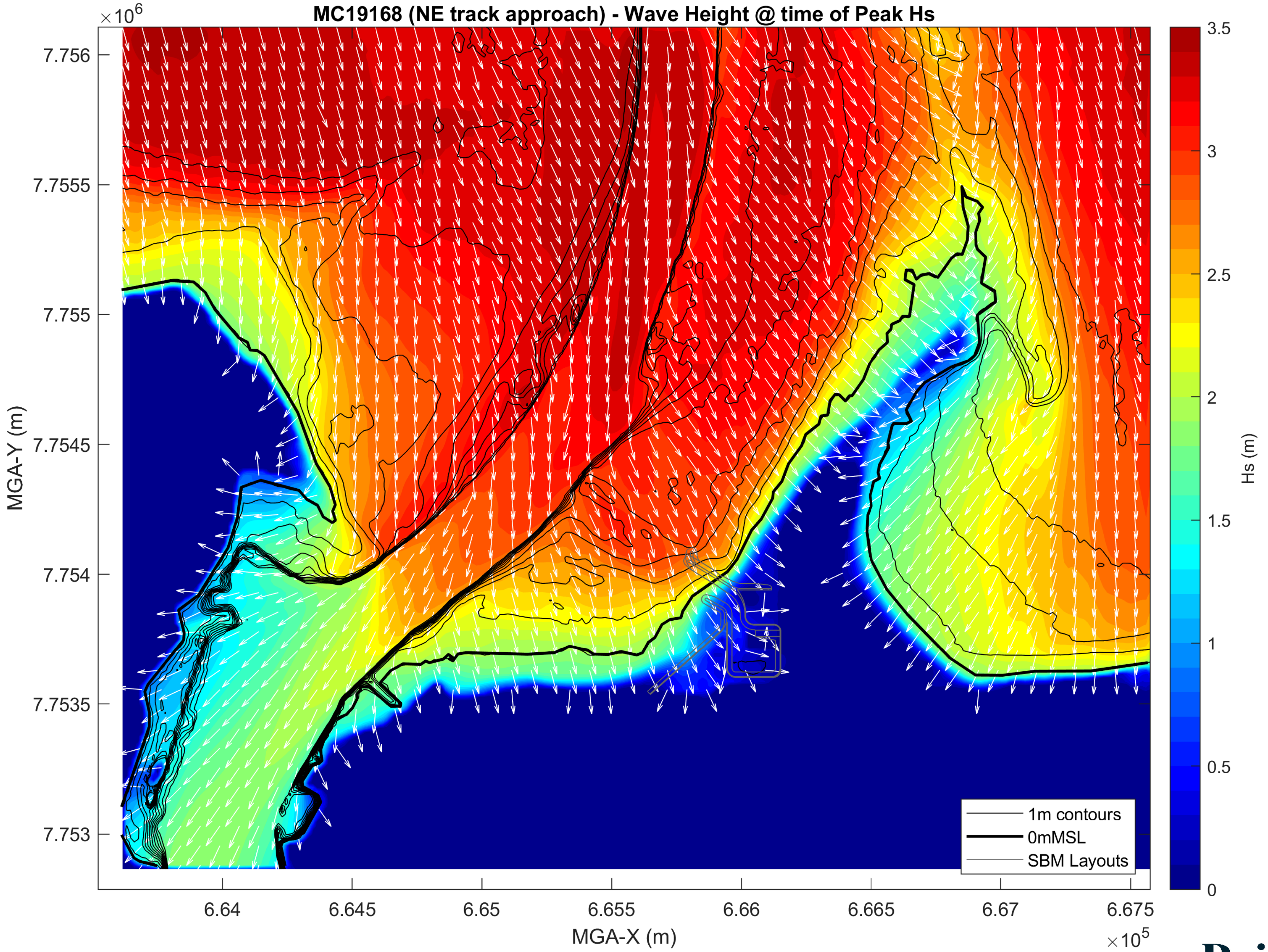

MC5430 (NNW track approach) - Wave Height @ time of Peak Hs
×10^6
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
MGA-X (m)
×10^5
1m contours
0mMSL
SBM Layouts
3.5
3
2.5
2
1.5
1
0.5
0
Hs (m)

Baird.



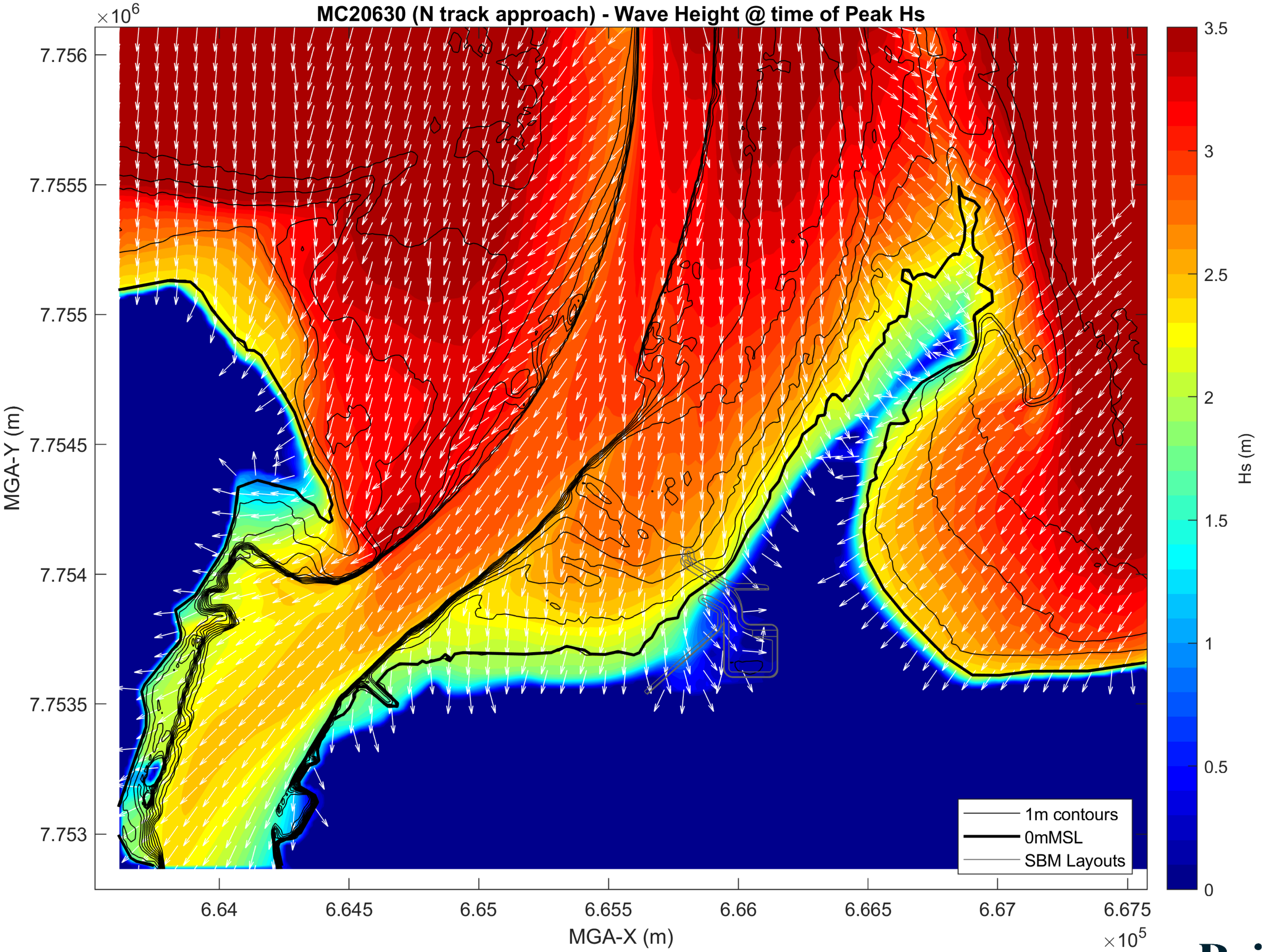
MC10785 (NNW track approach) - Wave Height @ time of Peak Hs
$\times 10^6$
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
$\times 10^5$
MGA-X (m)
1m contours
0mMSL
SBM Layouts
3.5
3
2.5
2
1.5
1
0.5
0
Hs (m)

Baird.



MC19168 (NE track approach) - Wave Height @ time of Peak Hs
×10^6
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
×10^5
MGA-X (m)
1m contours
0mMSL
SBM Layouts
3.5
3
2.5
2
1.5
1
0.5
0
Hs (m)

Baird.



Baird.

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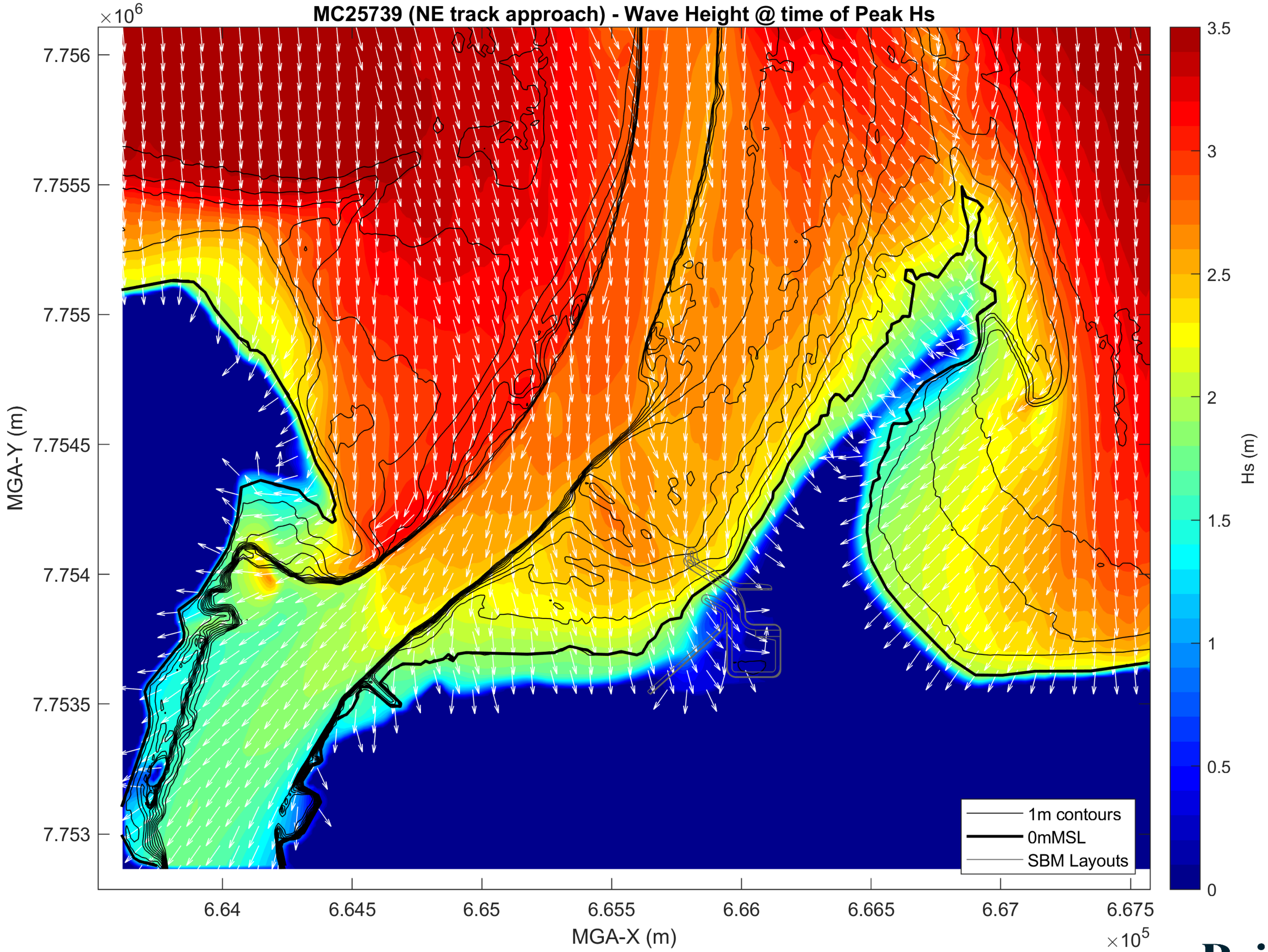
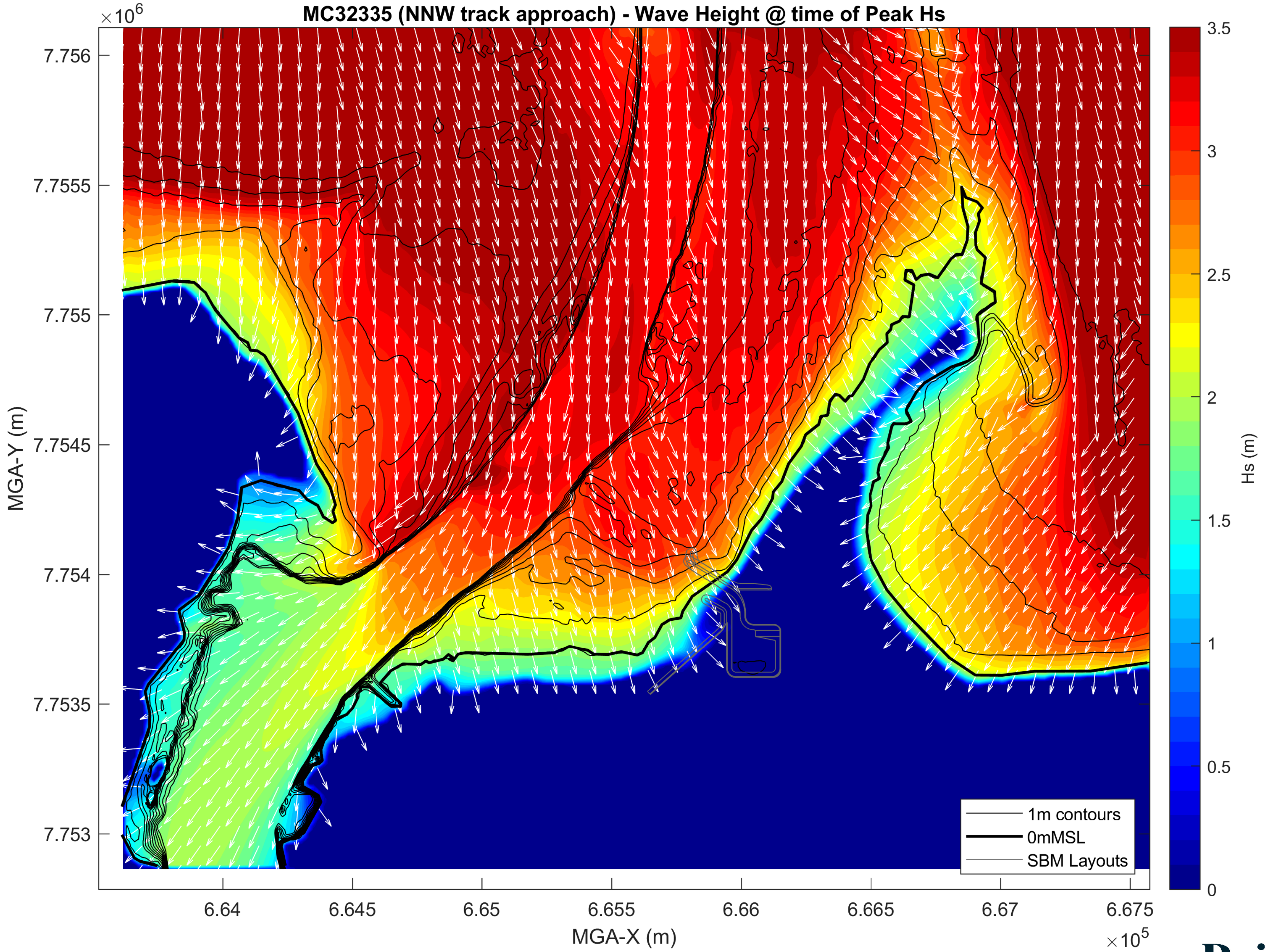
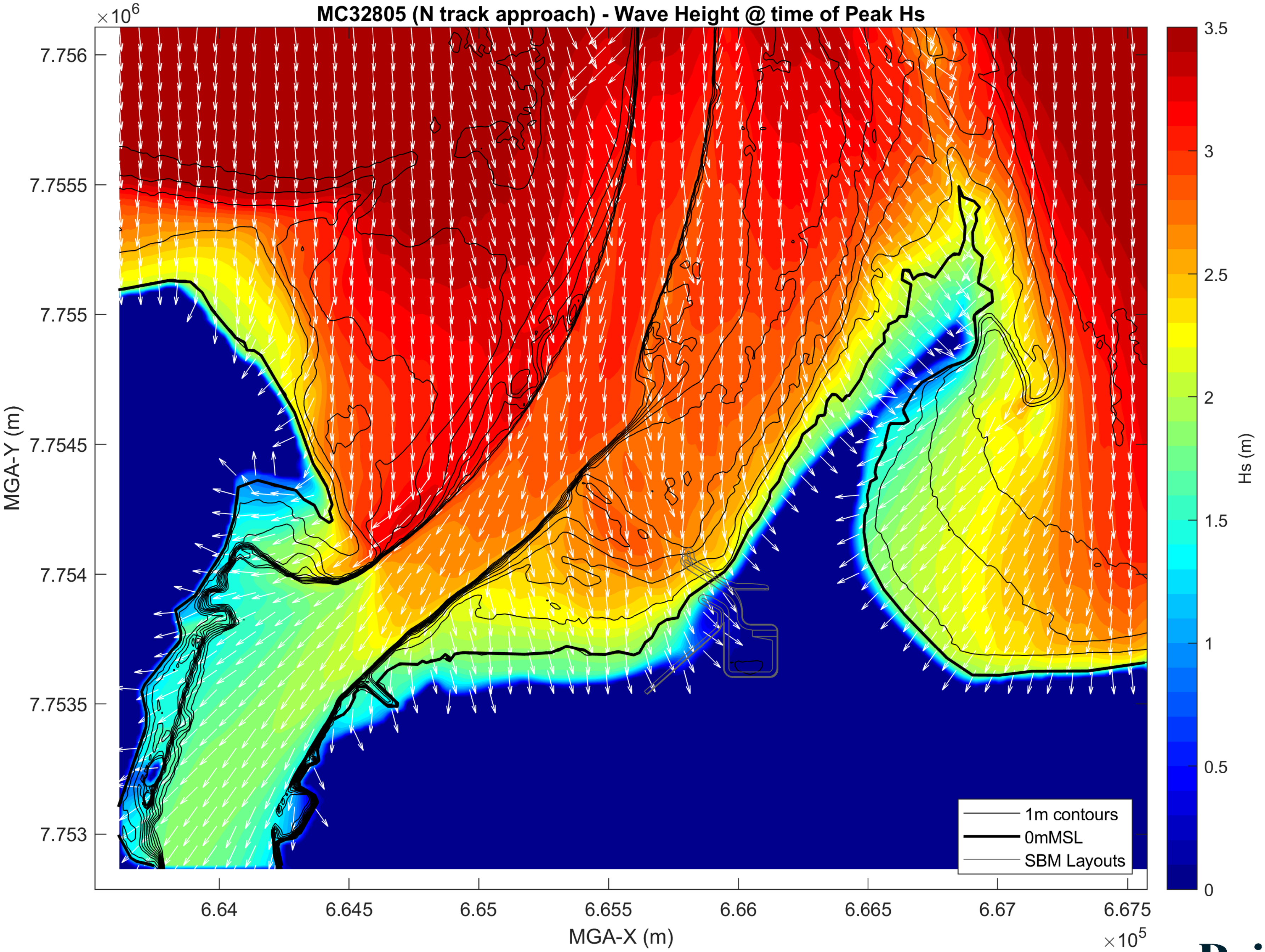


MC25739 (NE track approach) - Wave Height @ time of Peak Hs
×10^6
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
×10^5
MGA-X (m)
1m contours
0mMSL
SBM Layouts
Hs (m)
3.5
3
2.5
2
1.5
1
0.5
0

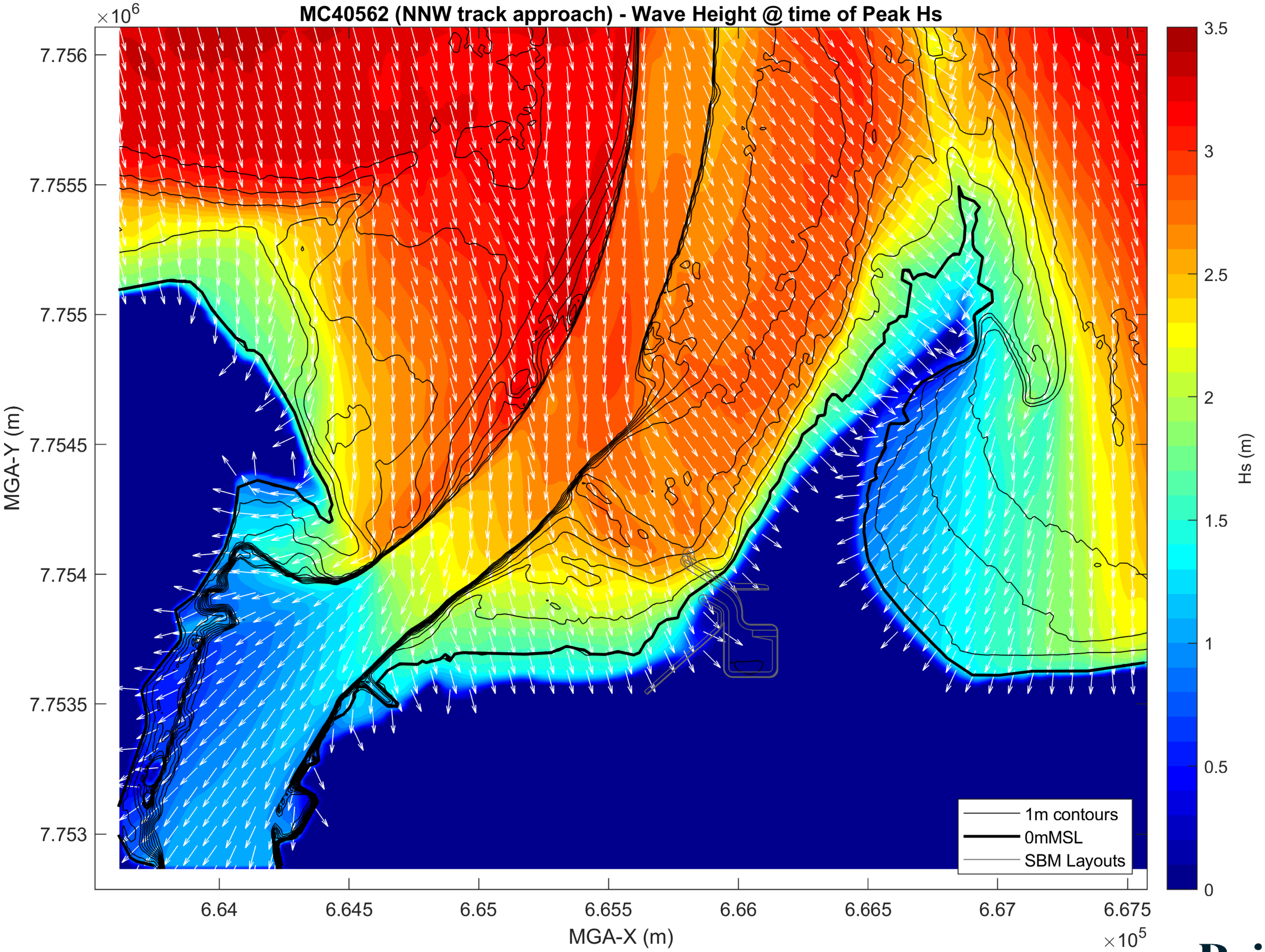

MC32335 (NNW track approach) - Wave Height @ time of Peak Hs
×10^6
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
MGA-X (m)
×10^5
1m contours
0mMSL
SBM Layouts
3.5
3
2.5
2
1.5
1
0.5
0
Hs (m)

Baird.

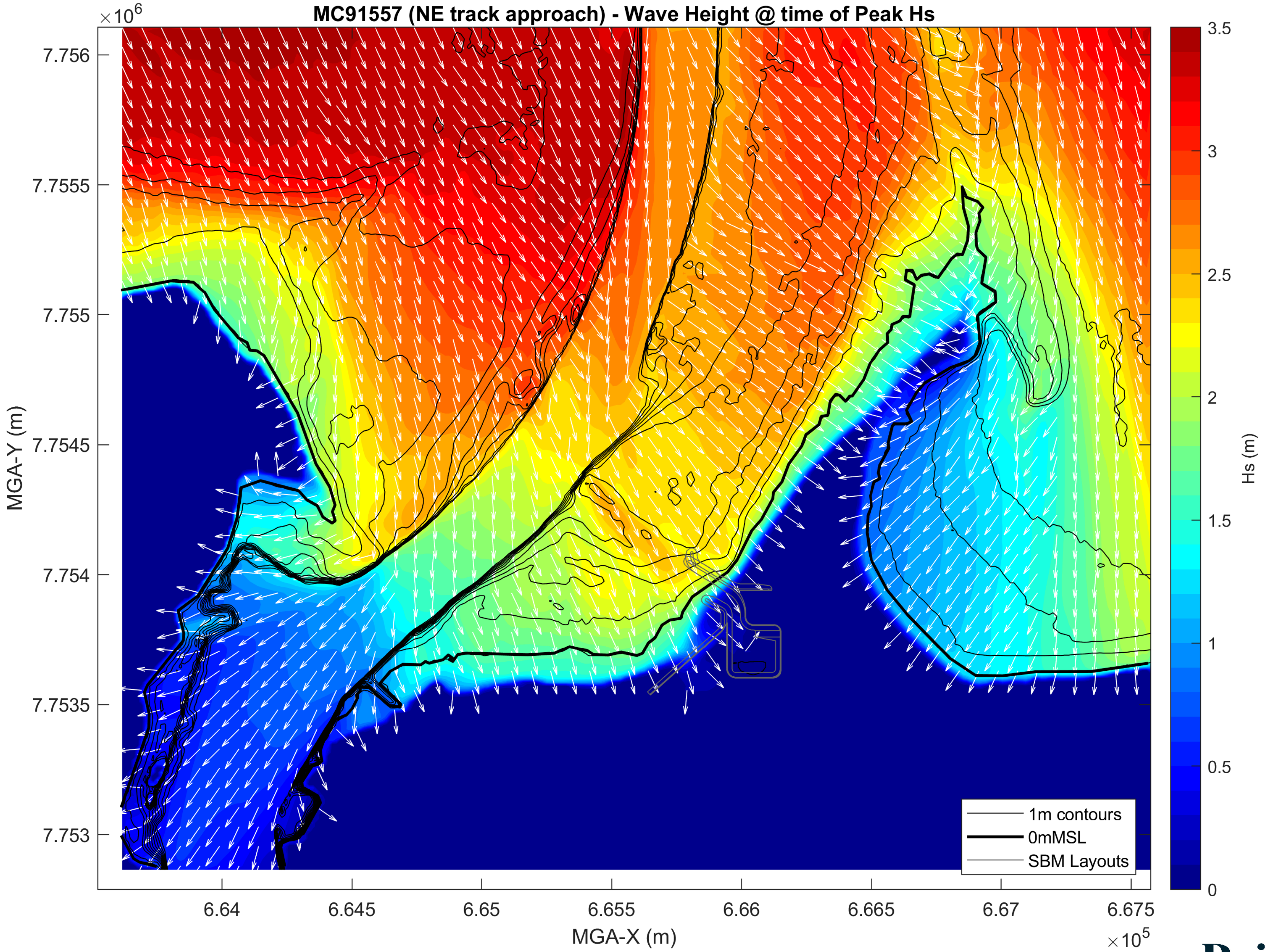


MC32805 (N track approach) - Wave Height @ time of Peak Hs
×10^6
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
MGA-X (m)
×10^5
1m contours
0mMSL
SBM Layouts
3.5
3
2.5
2
1.5
1
0.5
0
Hs (m)

Baird.



MC40562 (NNW track approach) - Wave Height @ time of Peak Hs
$\times 10^6$
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
MGA-X (m)
$\times 10^5$
1m contours
0mMSL
SBM Layouts
3.5
3
2.5
2
1.5
1
0.5
0
Hs (m)



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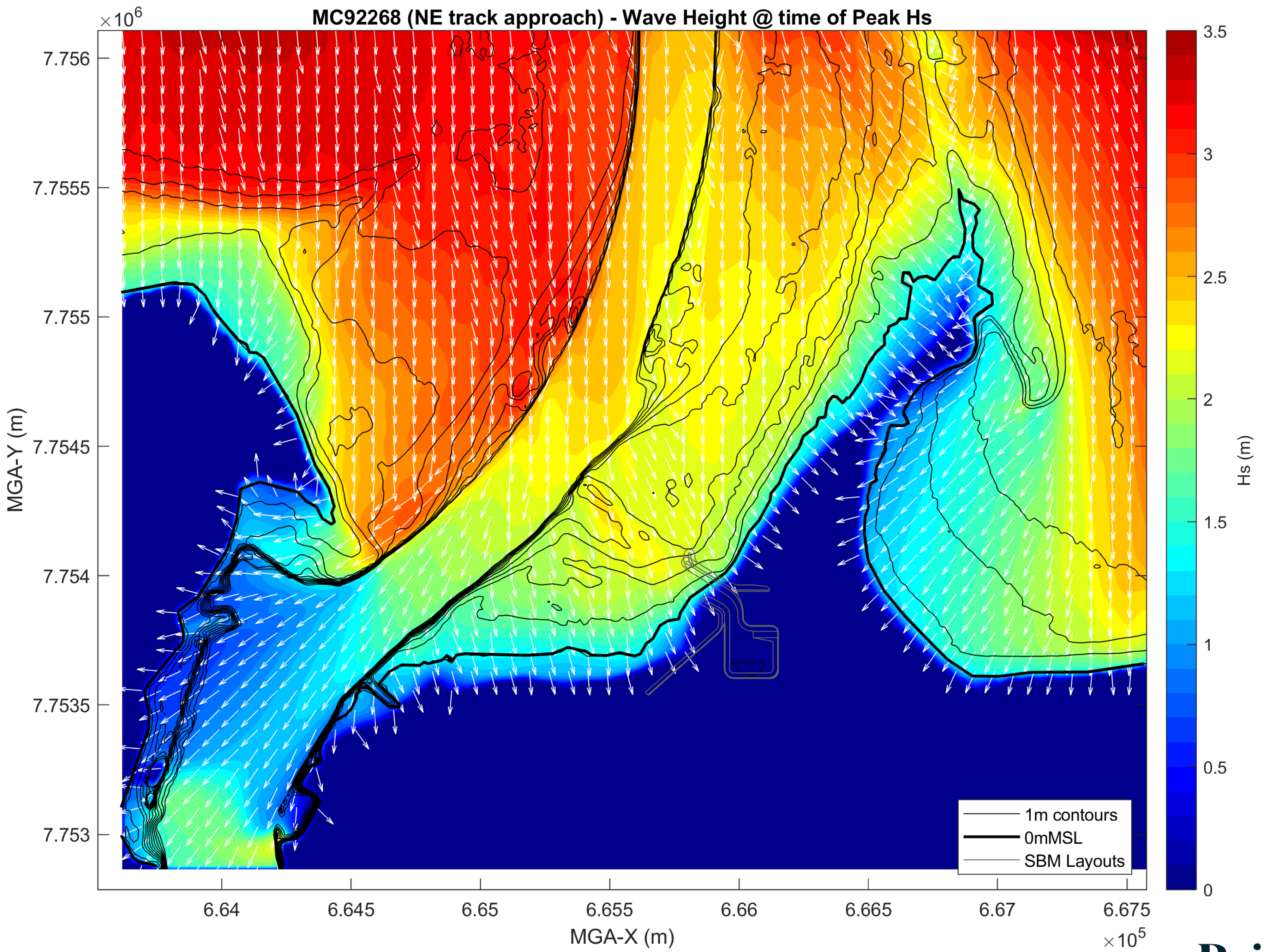
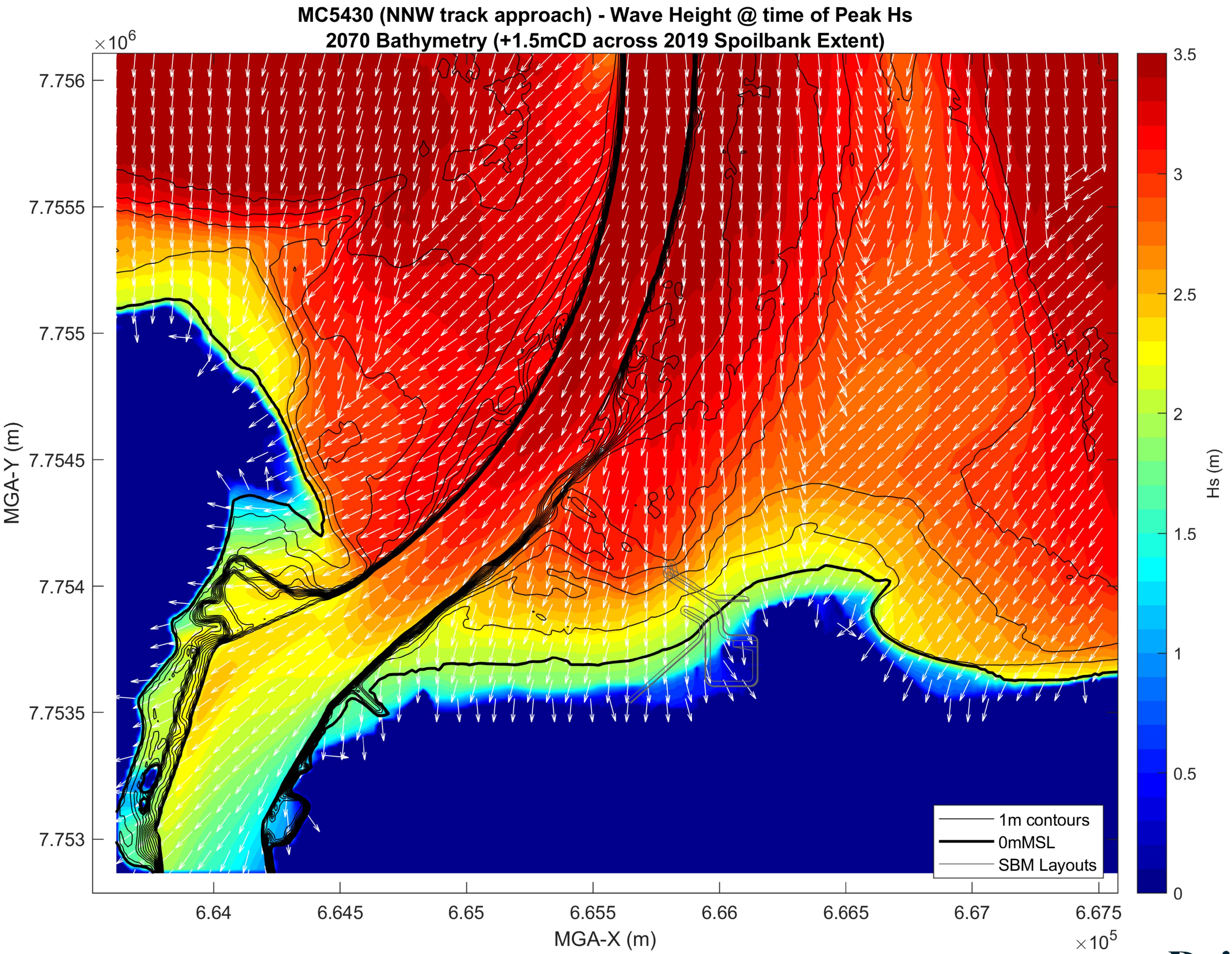
13143.101 | Aug-2019

N:\Projects\13143.101_DoT_SpoilbankMarina\06_Models\FWF\Figures\MC91557_HsMap_PkTS_wDirM_v3.pdf

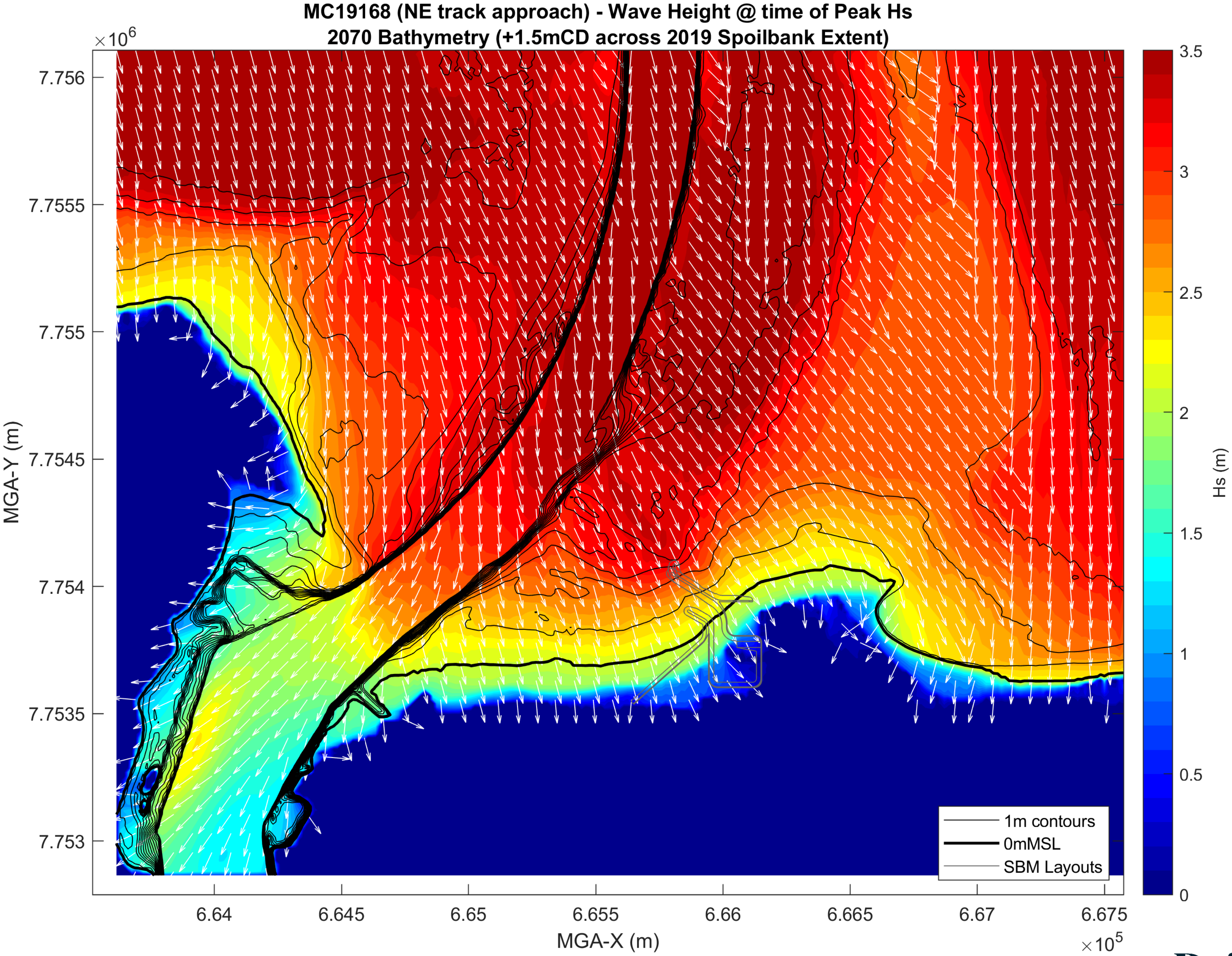


MC92268 (NE track approach) - Wave Height @ time of Peak Hs
×10^6
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
MGA-X (m)
×10^5
1m contours
0mMSL
SBM Layouts
Hs (m)
3.5
3
2.5
2
1.5
1
0.5
0

Baird.



MC5430 (NNW track approach) - Wave Height @ time of Peak Hs
2070 Bathymetry (+1.5mCD across 2019 Spoilbank Extent)
×10^6
7.756
7.7555
7.755
7.7545
7.754
7.7535
7.753
MGA-Y (m)
6.64
6.645
6.65
6.655
6.66
6.665
6.67
6.675
MGA-X (m)
×10^5
1m contours
0mMSL
SBM Layouts
3.5
3
2.5
2
1.5
1
0.5
0
Hs (m)



13143.101 | 04-Nov-2019
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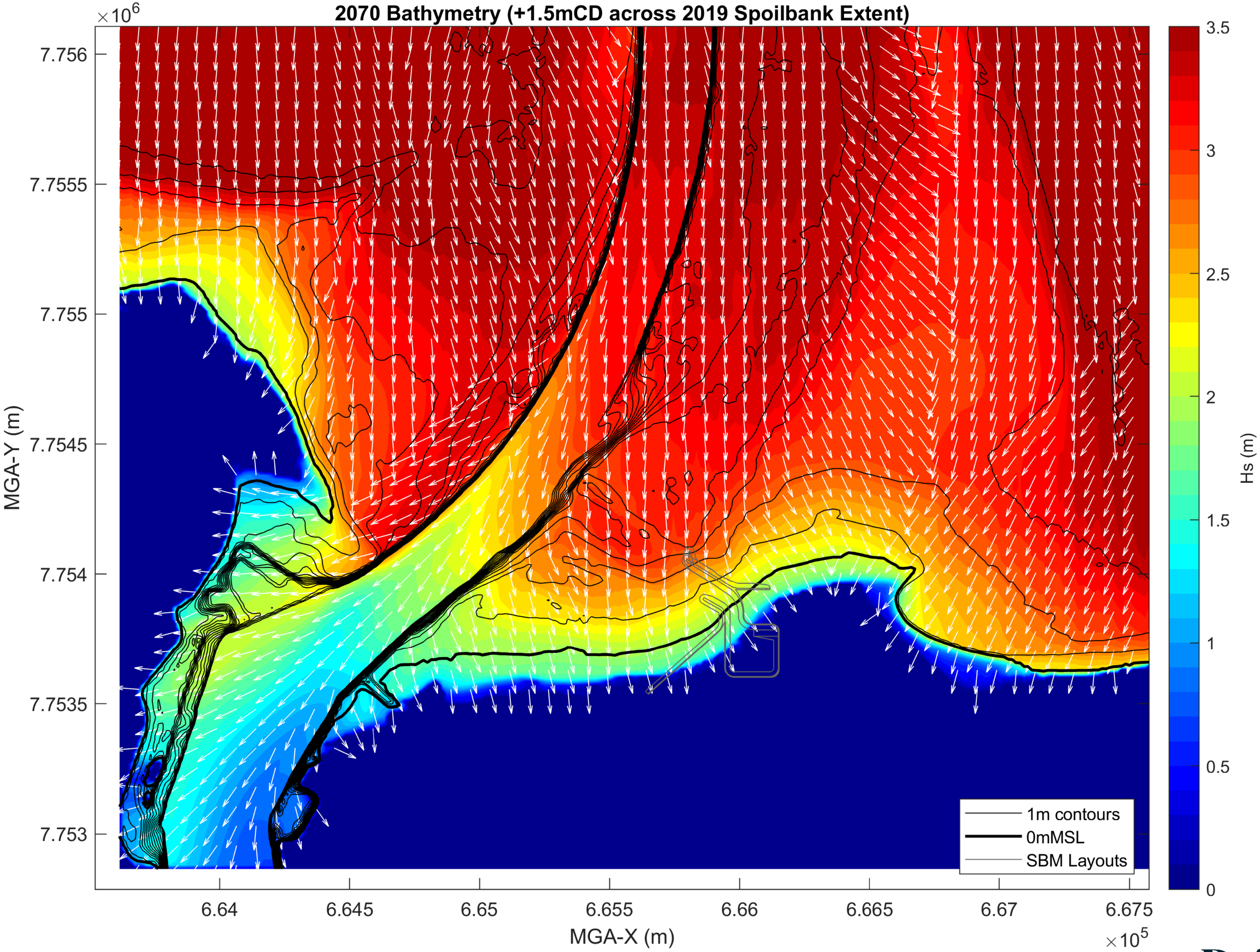
MC32335 (NNW track approach) - Wave Height @ time of Peak Hs
2070 Bathymetry (+1.5mCD across 2019 Spoilbank Extent)



13143.101 | 04-Nov-2019
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