## Associated British Ports

# Immingham Eastern RoRo Terminal

## Preliminary Environmental Information:
## Appendix 7.1 Numerical Model Calibration

### January 2022





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# Document Information

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# 1 Numerical Model Calibration

## 1.1 Introduction

1.1.1 ABPmer has been commissioned to undertake hydrodynamic, sediment transport, dredge plume and wave studies to support the development and consenting of a new roll-on/roll-off (Ro-Ro) facility within the Port of Immingham. The site for the proposed Terminal lies within the eastern sector of the Port and will be designed to service the embarkation and disembarkation of principally commercial and automotive traffic.

1.1.2 The he marine elements of the project comprise:

- An approach jetty from the shore;
- A linkspan with bankseat;
- Two floating pontoons with guide piles or articulated restraint arms;
- Two separate finger piers with up to two berths each; and
- The capital dredge of the new berth pocket, and disposal of dredged material at sea.

1.1.3 To assist with the study, a numerical hydrodynamic model has been set up and calibrated. This report provides a description of the modelling tools that have been applied in the assessment and details the setup, calibration and validation of the individual models. This exercise demonstrates that the hydrodynamic model provides a realistic representative of the existing hydrodynamic conditions that occur at the site, and the model provides a suitable basis to examine the sediment transport regime at the sites and the dispersion of material released from the associated dredging operations. In addition, a spectral wave (SW) model has also been set up and calibrated to assist with the assessment.

1.1.4 This calibration report is sectioned as follows:

- Section 2: Describes the setup and calibration of the hydrodynamic model;
- Section 3: Describes the setup of and verification of the sediment transport model;
- Section 4: Describes the setup of the dredging operations dispersion model; and
- Section 5: Describes the setup of and verification of the spectral wave model.

# 2 Hydrodynamic Model

## 2.1 Introduction

2.1.1 The hydrodynamic modelling for this study has been completed using the state-of-the-art Danish Hydraulic Institute (DHI) software package MIKE21FM (Flexible Mesh), which has been developed specifically for applications within oceanographic, coastal and estuarine environments.

2.1.2 This project utilises the MIKE21 Hydrodynamic (HD) model to simulate the variations in water level and two-dimensional depth averaged flow within the study area. The model has been setup to examine how the proposed Project will affect the hydrodynamics and, in turn, the sediment regime within this area of the Humber. The model is also used to examine the advection and dispersion of material released from the associated dredging operations.

2.1.3 The model setup, calibrations and validation are described in the following sections.

## 2.2 Model grid

2.2.1 The HD model extent is based on ABPmer's existing numerical model of the region, encompassing the entire Humber Estuary, and an associated area offshore to enable suitable boundary conditions to be applied (Figure 1).

2.2.2 The model grid uses the flexible mesh feature of the MIKE 21 software, allowing the grid resolution to vary throughout the model domain. This allows key areas of interest to be covered with a higher resolution grid, increasing the level of detail and precision. Offshore areas are then given a coarser resolution, aiding computational efficiency. Within this model grid, the offshore extents of the Humber, near the model boundaries, have a resolution of approximately 800 m. At the entrance to the Humber, this reduces to approximately 700 m, and continues to reduce through the estuary, reaching a resolution of around 75 m at Hull Bend. At its finest, the grid has a resolution of approximately 20 m around the proposed dredge pocket and berth. An overview of the mesh resolution is provided in Figure 1.


**Figure 1. Overall model extent (top), resolution at key area of interest (bottom)**

## 2.3 Model bathymetry

2.3.1 The bathymetric datasets used in the creation of the model mesh consist of a combination of survey data provided by ABP for the study in and around Immingham. This data consists of surveys from August 2019; and March, April and May 2021. An overview of the coverage of this data is shown in Figure 2.

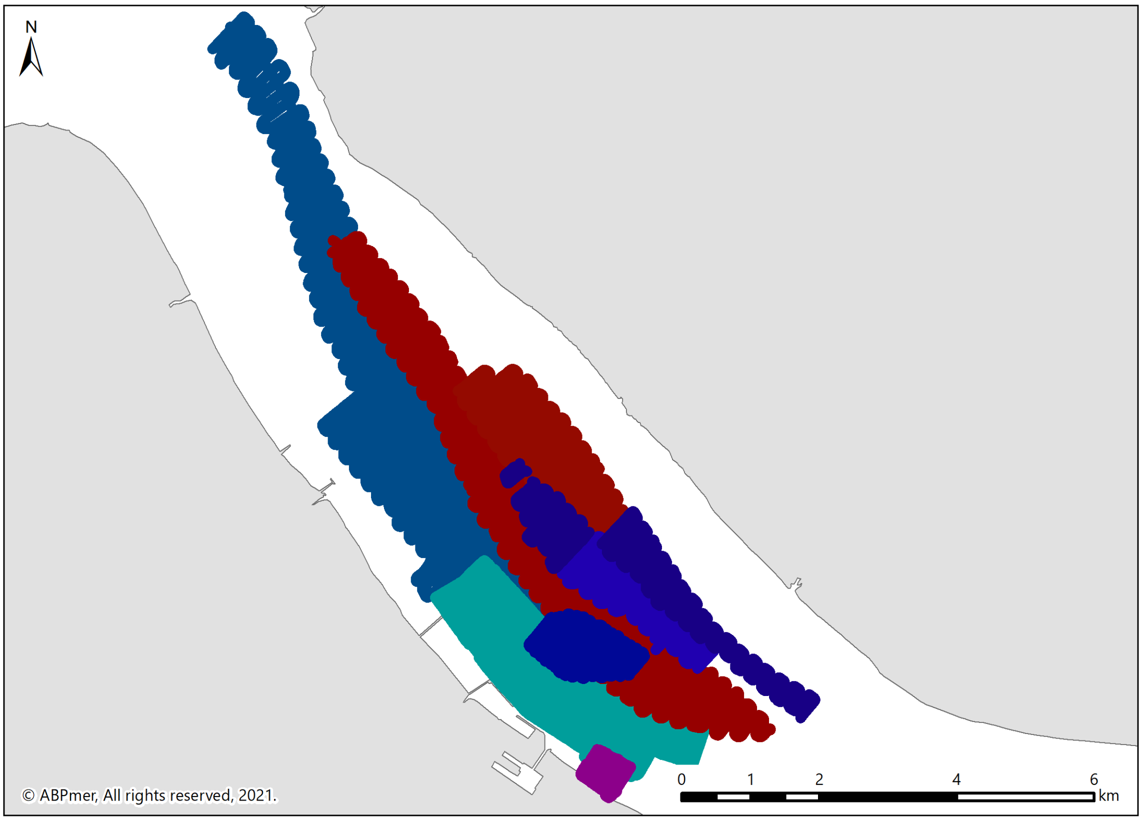


**Figure 2. Overview of extent of bathymetry data provided by ABP for the study**

2.3.2 In order to fill the gaps in data, further survey data collected by ABPmer in February 2020 for the area around Hull and Hull Bend has also been used, along with topographic LiDAR data from the Environment Agency (EA) Open Data portal, and MIKE C-MAP.

2.3.3 All data (where necessary) has been converted to a vertical reference of Mean Sea Level (MSL), using the UKHO VORF.

2.3.4 Whilst it is known that the Humber is a dynamic system that can experience significant changes to channels and shoals, the area between Immingham and Grimsby is the deepest and most stable area of the estuary (ABPmer, 2021). Therefore, for this study, only one bathymetric dataset has been used.

## 2.4 Model boundary conditions

2.4.1 Tidal boundaries have been applied along all four outer edges of the model, offshore of the Humber (Figure 3). The boundary definitions used in the model are derived from ABPmer's UK Tide and Surge regional hindcast model (ABPmer, 2017). This regional model, which covers the entire northwest European continental shelf, has been extensively calibrated against available tide gauge and current meter datasets and has been successfully used to provide boundary conditions for a range of high-resolution local models.

2.4.2 For this study, which is focussed on predicting impacts of the Project on mean spring and neap tidal conditions, tide-only boundaries (with no meteorological surge component) have been used to drive surface elevations and resultant tidal flows through the Humber Estuary.

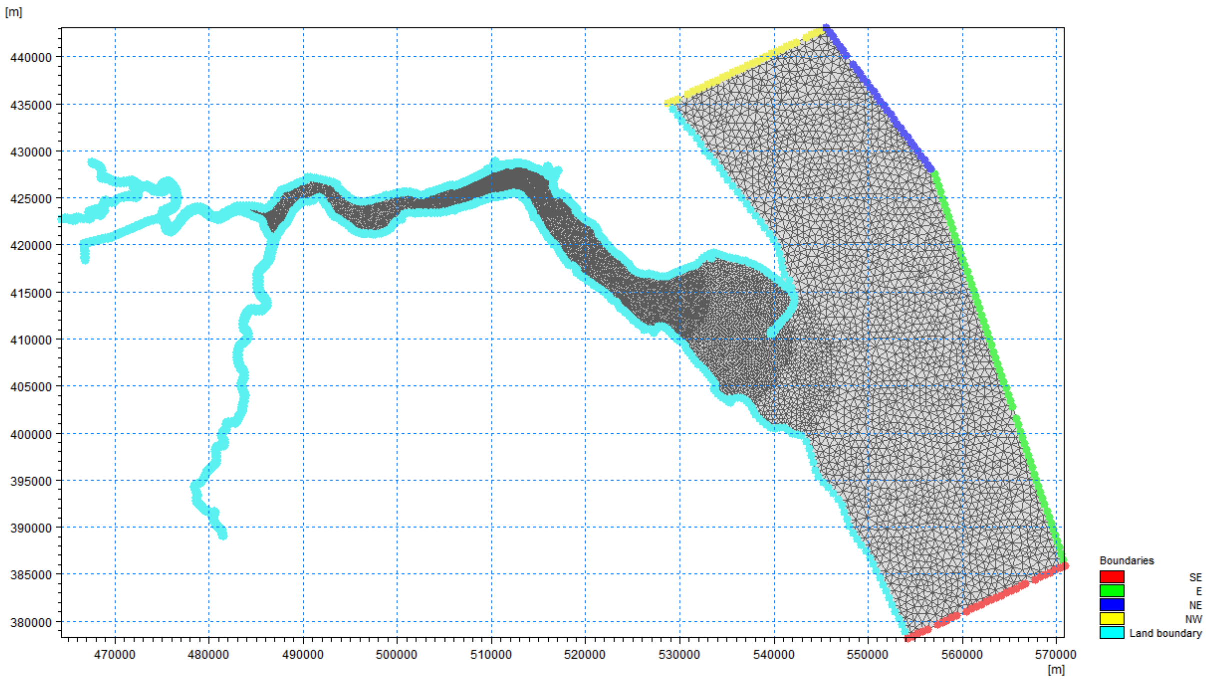


**Figure 3. HD model boundaries**

## 2.5 Bed roughness

2.5.1 Bed roughness in the model has a large influence on the way in which the water moves through a particular area, affecting both tidal range and phase, as well as the speed and directions of tidal currents. It describes the friction from the seabed 'felt' by moving water and is therefore a key variable in the calibration of a model.

2.5.2 The bed roughness map from ABPmer's existing model of the region was initially adopted for the model and a series of amendments were then made to this, as part of the model calibration process. These amendments were made to help improve the ability of the model to reproduce the measured flow conditions at the site and the wider hydrodynamic regime through the wider estuary.

2.5.3 The bed roughness map utilised in the calibrated model is provided in Figure 4.

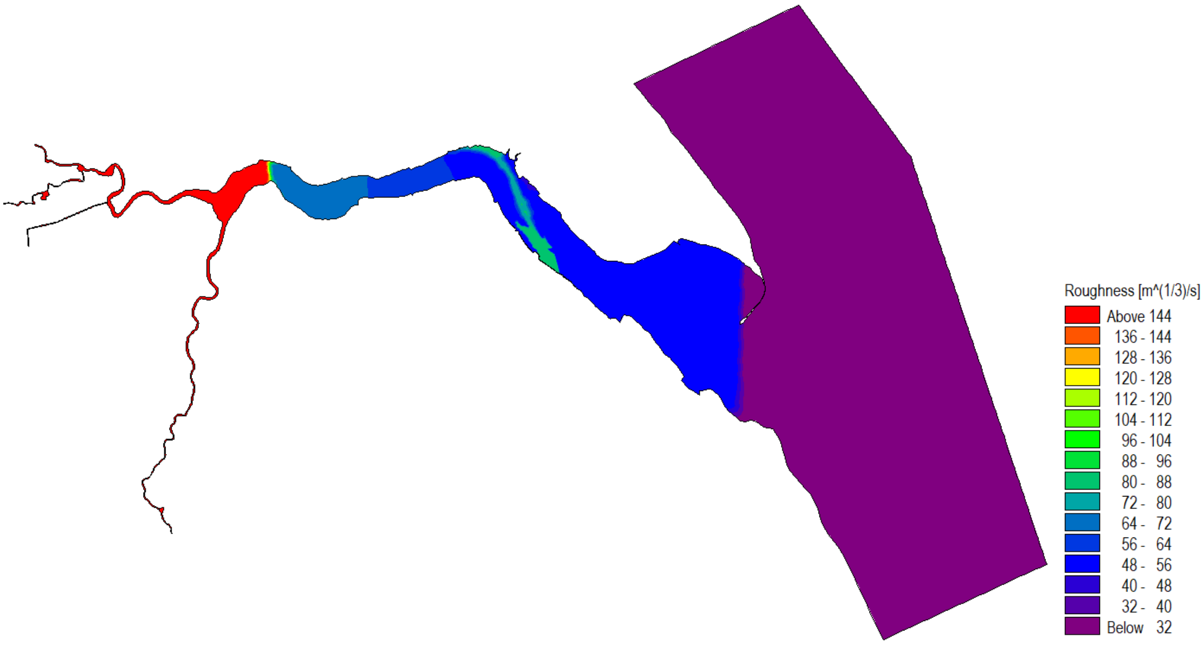


**Figure 4. Bed roughness map utilised in the calibrated model**

## 2.6 Calibration and validation data

### Water levels

2.6.1 As part of long-term development strategies, Associated British Ports (ABP) commissioned ABPmer to undertake a hydrodynamic survey surrounding Immingham Dock. An Acoustic Wave and Current (AWAC) device, combined with Salinity and Turbidity sensors were deployed on a seabed frame at a subtidal location inshore of the main Oil Terminal. This data, referred to in this report as AWAC 1, has been used for the calibration of this model. This has been carried out over a spring-neap period (26/05/20 – 05/06/20). Alongside this, National Tidal and Sea Level Facility (NTSLF) tide gauge data at Immingham has also been used. This is a tidally derived component of the measured water level. In addition to this, Admiralty predicted water levels at five sites within the estuary were obtained using TotalTide, from The United Kingdom Hydrographic Office (UKHO). These harmonically derived data sets are referred to as 'measured' or 'observed' data in the discussion on model performance.

2.6.2 Model validation has been carried out against a second AWAC deployment, also carried out as part of the long-term development strategies, immediately of Berth 2 of the Humber International Terminal (HIT), (AWAC 2). Validation has been carried out over a spring-neap tidal period (30/08/20 – 09/09/20). As well as the data collected at AWAC 2, NTSLF and Admiralty predicted tidal levels have also been used for the same period.

2.6.3 The model calibration and validation periods were chosen as it represents average tidal conditions for the area. Levels have been analysed both visually and statistically following the guidelines outlined in Section 2.7.

2.6.4 A summary of the water level data used in the model calibration and validation is provided in Table 1. The locations of the sites are provided in Figure 5.

**Table 1. Water level calibration and validation data**

| Location | Source | Easting | Northing | Duration | Calibration or Validation |
|---|---|---|---|---|---|
| AWAC 1 | Measured AWAC Data | 520750 | 416397 | 15/11/19 to 05/06/20 | Calibration |
| AWAC 2 | Measured AWAC Data | 518803 | 417905 | 05/06/20 to 13/09/20 | Validation |
| Spurn Head | Admiralty prediction | 540066 | 411745 | 25/05/20 to 13/09/20 | Calibration and validation |
| Grimsby | Admiralty prediction | 528981 | 411469 | 25/05/20 to 13/09/20 | Calibration and validation |
| Immingham | NTSLF Tide Gauge | 520064 | 416699 | 25/05/20 to 13/09/20 | Calibration and validation |
| Hull - King George Dock (KGD) | Admiralty prediction | 514808 | 427683 | 25/05/20 to 13/09/20 | Calibration and validation |
| Hull - Albert Dock | Admiralty prediction | 508300 | 426966 | 25/05/20 to 13/09/20 | Calibration and validation |

## Current data

2.6.5 The predicted flows at the site were calibrated against measured flow data from the AWAC 1 deployment over the over a spring-neap period 26/05/20 to 05/06/20. Modelled flows were validated against measured flow data from the AWAC 2 deployment over a spring neap period 30/08/20 – 09/09/20. Details of the deployments are provided in Table 1.

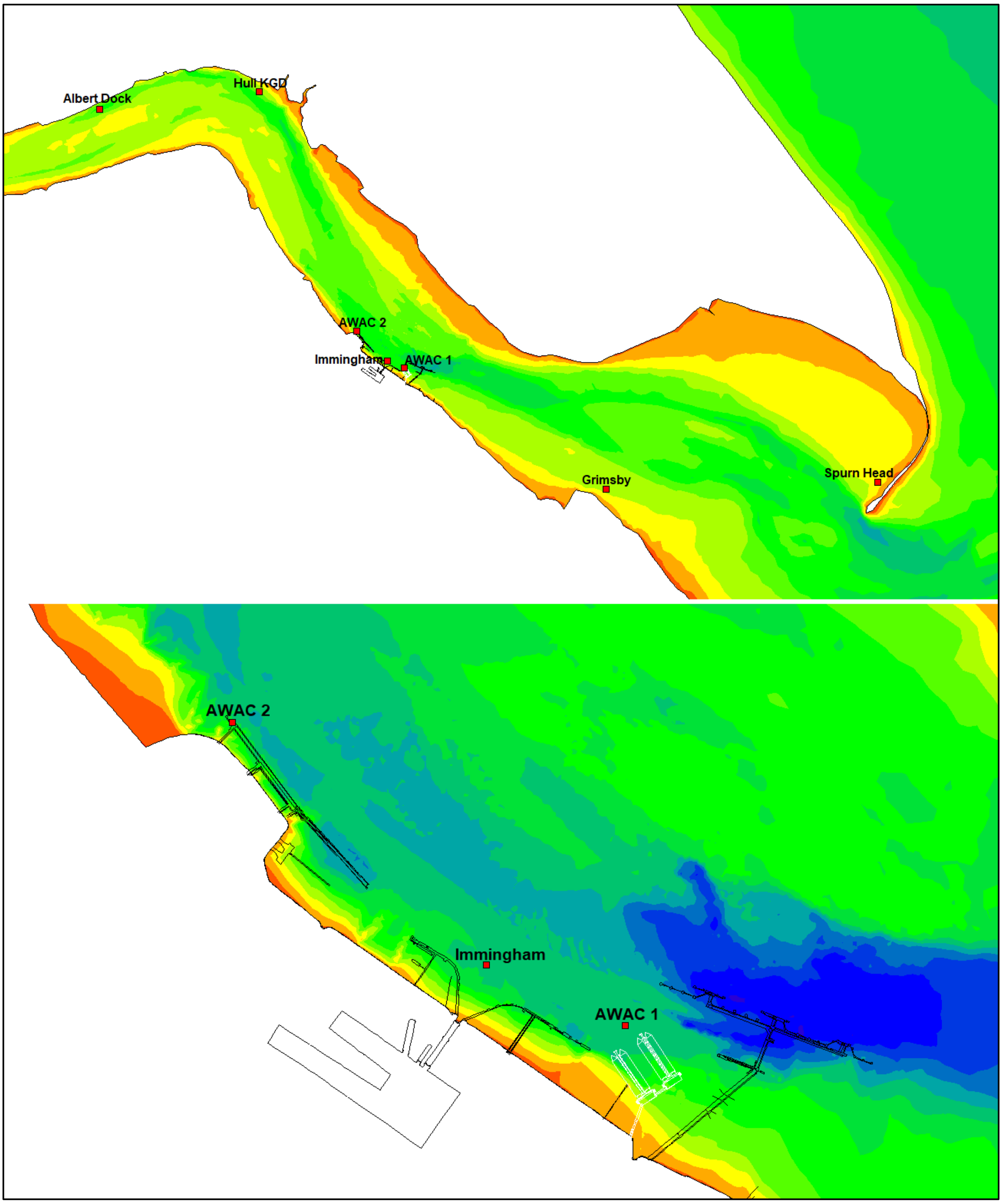


**Figure 5. Geographical location of calibration data points. Red outline indicates proposed Ro-Ro facility**

## 2.7 Model performance metrics and guidelines

2.7.1 The metrics used to assess the hydrodynamic model performance are set out in Table 2. In addition to the target metrics, the model should also simulate any specific features of the tidal shape or flow measurements, such as tidal stands, specific shapes of the flood and ebb profiles and relative flood to ebb flow speed asymmetry. The performance of the model is therefore examined and assessed through a combination of quantitative and qualitative assessments.

2.7.2 A level of discrepancy between the observations and model predictions is to be accepted and it is considered unnecessary to further justify discrepancies between modelled and measured values that lie within the target metrics. Larger discrepancies may be tolerated in cases where accuracy of the observational data is questionable. If such discrepancies arise, further discussion is required. This discussion should examine the relative importance of the model's ability to capture the specific feature identified and how this will affect the modelling results given the intended use of the model.

**Table 2. Performance metrics for hydrodynamic models**

| Metric | Description | Target | Recommended By |
|---|---|---|---|
| **Water Levels** | | | |
| Mean surface elevation difference (high and low water level) | Calculated as the mean difference (bias) in water level at high and low water (model minus observed value) for a spring and neap tidal period. The mean difference is also expressed as a percentage of the mean tidal range; | ± 0.1 m *(or to within 10% and 15% of spring and neap tidal ranges respectively)* *1 | ABPmer, 2014; Bartlett, 1998 |
| Time adjusted fit | This is the phase correction required to yield the minimum difference between the modelled and observed water levels at all timesteps for a spring and neap tidal period and indicates any phase lag in the model; | ±15 minutes in coastal areas,<br><br>±25 minutes in estuaries | ABPmer, 2014 |
| RMSE surface elevation difference | This value is calculated as the RMS value after the application of the time adjusted fit. Values are calculated over a defined period. | 0.2 m for A (Design model)<br><br>0.25 m for B (Appraisal model) | CH2M, 2015 (Environment Agency LEMSA Guidance) |

| Metric | Description | Target | Recommended By |
|---|---|---|---|
| **Flows** | | | |
| Mean flow speed difference (at peak flows) | Calculated as the mean difference between the magnitudes at peak flow, over a defined period. This is also calculated as a percentage value relative to the maximum observed speed; | ±0.2 m/s (or 10% to 20%) | (ABPmer, 2014) (Bartlett, 1998) |
| Mean flow direction difference (at peak flows). | Calculated as the mean of the difference in flow direction recorded at times of peak flow, over a defined period; | ±10° of measured data | (ABPmer, 2014) |
| Time adjusted fit | This is the phase correction required to yield the minimum RMS differences between the modelled and observed flow speeds at all time-steps over a defined period | ±15 minutes in coastal areas, ±25 minutes in estuaries | (ABPmer, 2014) |
| Flow speed RMSE difference | This value is the RMS of flow speed difference and gives an indication of the agreement between modelled and measured flows throughout the tide and not just at the time of peak flow. This is calculated following the application of the time adjusted fit. Values are calculated over a defined period. | ±0.1 m/s of the peak flow for A (Design model) ±0.2 m/s of the peak flow for B (Appraisal model) | LEMSA |

1 The achievement of absolute levels where the tidal range is significant is likely to be difficult and comparison against tidal range is considered appropriate.

*

## 2.8 Model calibration

### Water Levels

2.8.1 The calibrated model has been compared against water levels at AWAC 1, the Immingham NTSLF gauge data, and the Admiralty tidal predictions for the spring-neap tidal period (26/05/20 – 05/06/20). Levels have been analysed both visually and statistically following the guidelines outlined in Section 2.7.

2.8.2 A quantitative statistical analysis of water levels at each of the locations is presented in Table 3, with visual comparisons provided in Figure 6 to Figure 11. The visual comparison shows that the general levels, shape and phasing of the tide is reproduced well. From Spurn Head to Hull, the tidal range increases as the tide propagates up through the estuary and this increase is also reproduced well by the model.

2.8.3 A review of the calibration metrics show that the model reproduces the measured water levels well through the estuary, particularly when considering these metrics relative to the tidal range, which is achieved well at all sites.

2.8.4 The time-adjusted fit values and the RMSE Surface Elevation difference at all locations are again within the target metrics.

**Table 3. Water level calibration statistics**

| Location (Calibration data source) | High Water Level Difference in m (and as % of Range) | Low Water Level Difference in m (and as % of Range) | Time Adjusted Fit (mins) | RMSE Surface Elevation Difference (m) |
|---|---|---|---|---|
| *Target* | *± 0.1 m (or to within 10% and 15% of spring and neap tidal ranges)* | *± 0.1 m (or to within 10% and 15% of spring and neap tidal ranges)* | *± 15 to 25 minutes* | *within 0.25 m* |
| AWAC 1 | -0.10 (-2%) | 0.00 (0%) | 22 | 0.21 |
| Spurn Head (TT) | -0.06 (-1%) | 0.09 (2%) | 23 | 0.18 |
| Grimsby (TT) | -0.06 (-1%) | 0.08 (2%) | 19 | 0.18 |
| Immingham (NTSLF) | -0.05 (-1%) | 0.09 (-2%) | 12 | 0.22 |
| Hull King George Dock (TT) | -0.06 (-1%) | 0.13 (2%) | 16 | 0.20 |
| Hull Albert Dock (TT) | -0.06 (-0%) | 0.14 (3%) | 20 | 0.23 |
| Note: Where guidance values are exceeded values are shown in Red. | | | | |

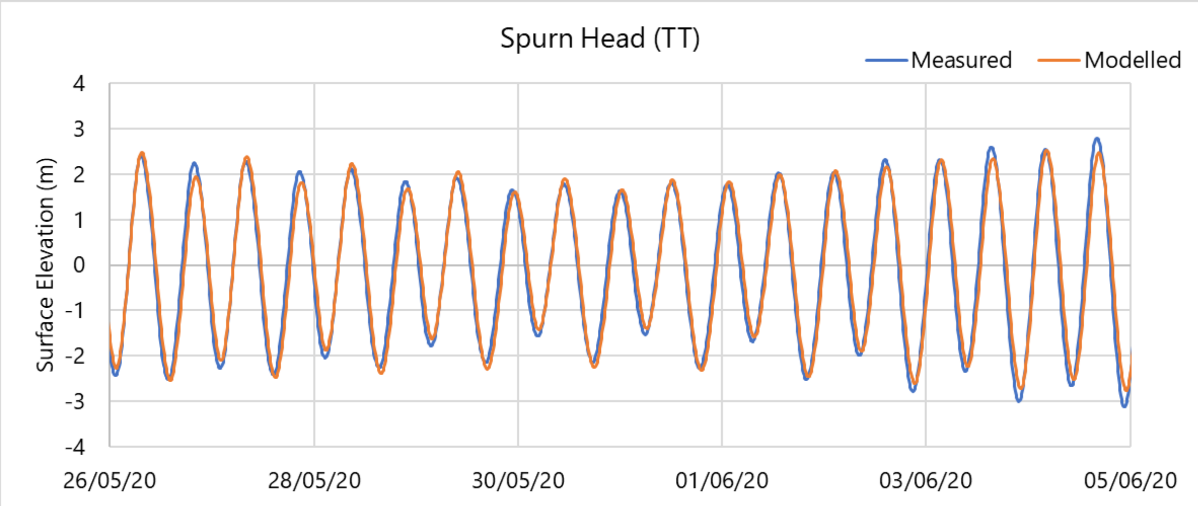


**Figure 6. Comparison of water levels against Admiralty tidal predictions at Spurn Head**

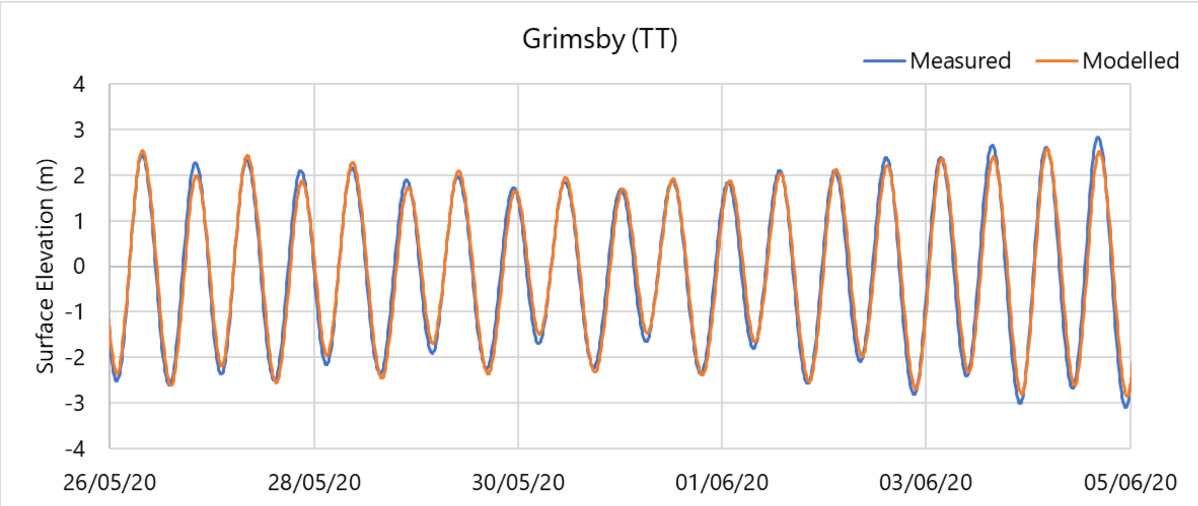


**Figure 7. Comparison of water levels against Admiralty tidal predictions at Grimsby**

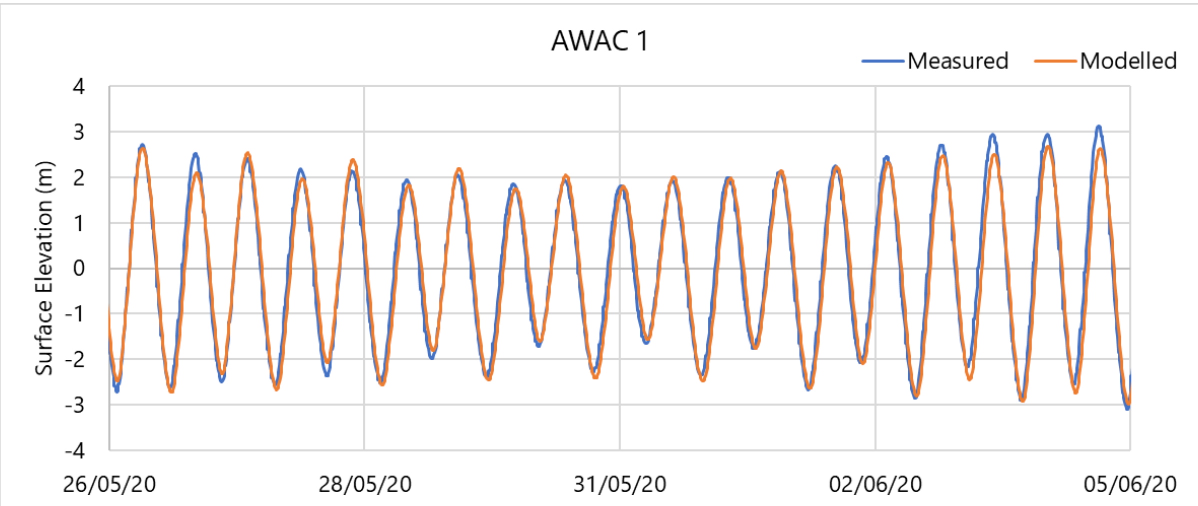


**Figure 8. Comparison of water levels at the Nordic AWAC deployment location (Immingham Oil Terminal)**

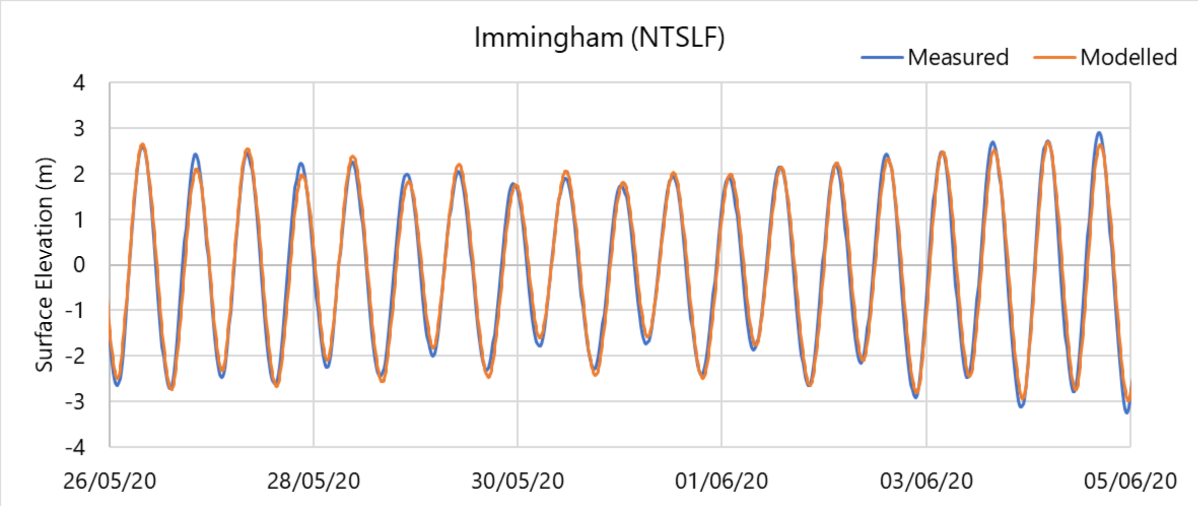


**Figure 9. Comparison of water levels at Immingham**

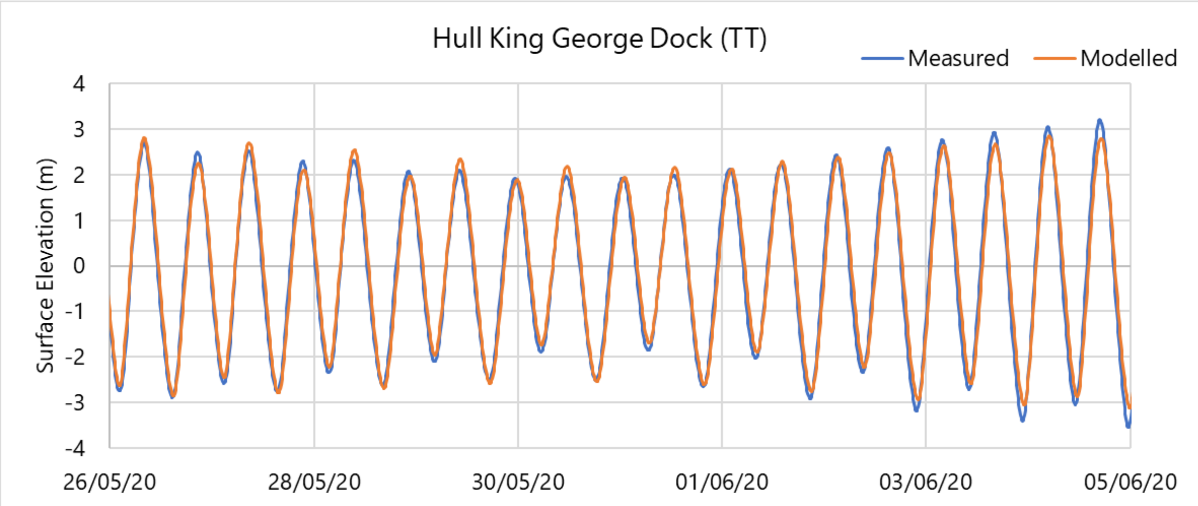


**Figure 10. Comparison of water levels against Admiralty tidal predictions at Hull King George Dock**

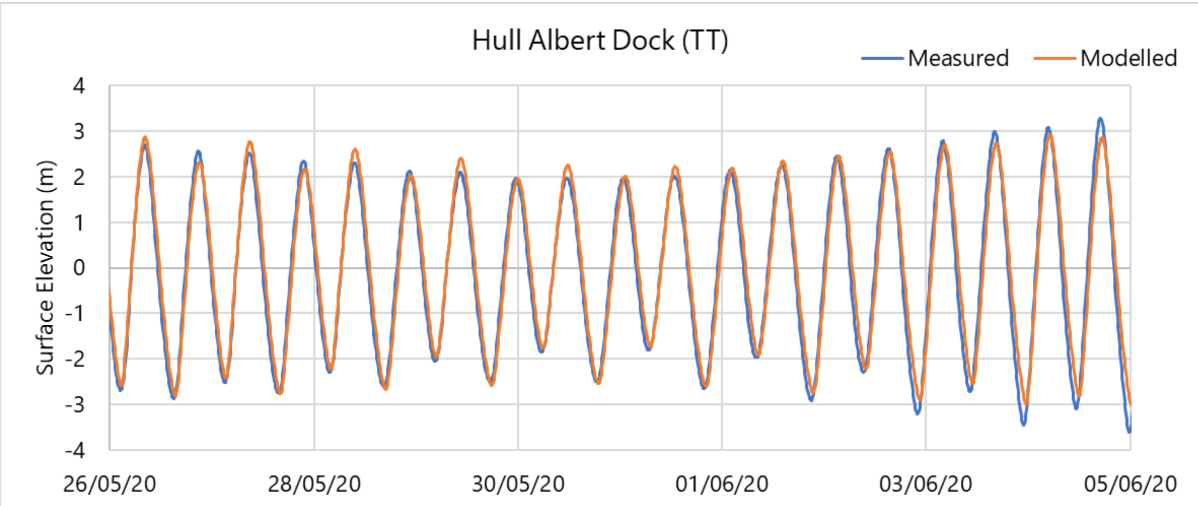


**Figure 11. Comparison of water levels against Admiralty tidal predictions at Hull Albert Dock**

## Currents

2.8.5 A comparison between the modelled flows and the measured depth averaged Nordic AWAC flow data is provided in Figure 12.

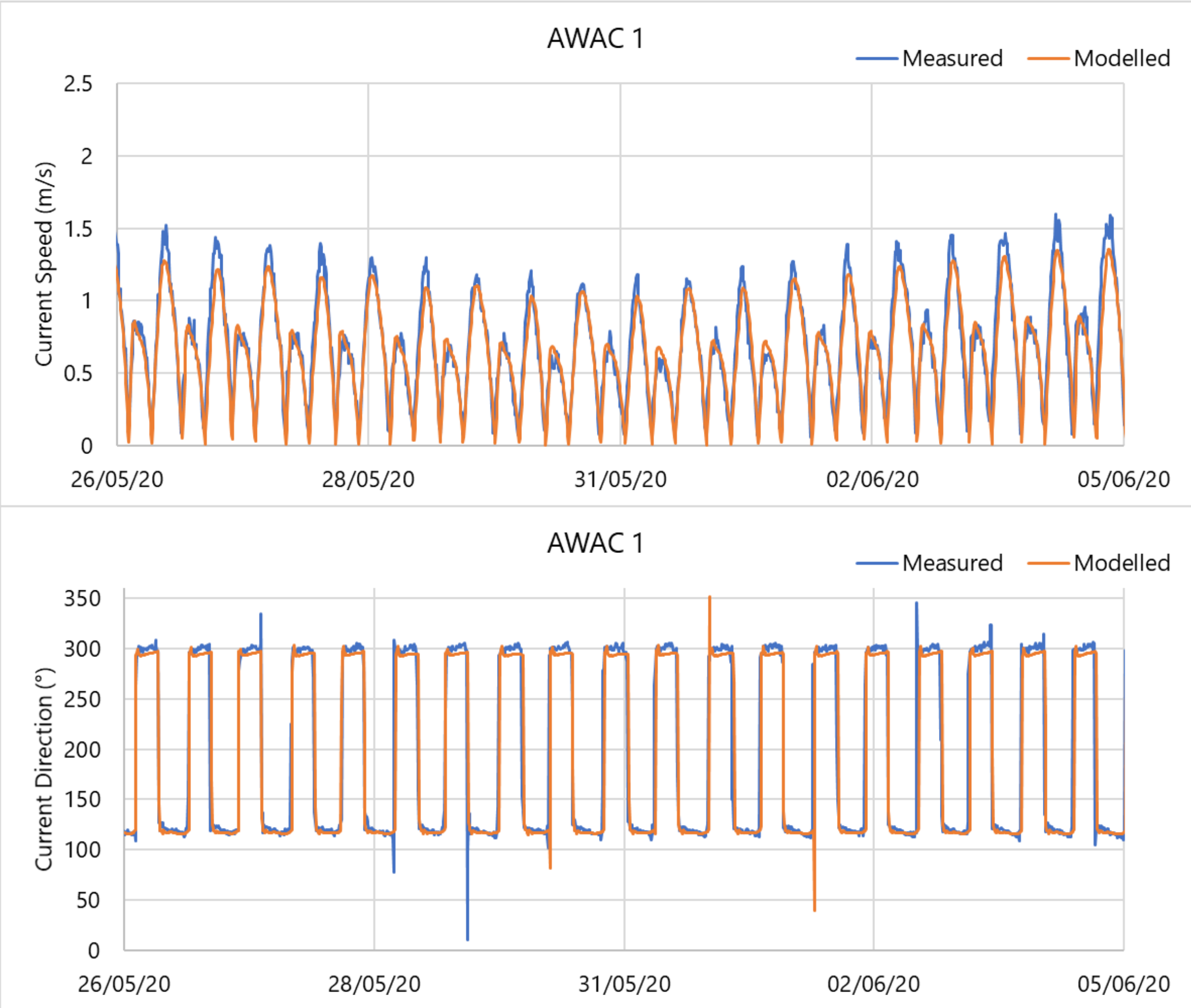


**Figure 12. Comparison of flow speed and direction at the Nordic AWAC deployment location (Immingham Oil Terminal)**

2.8.6 The model shows good agreement with the phasing of the flow on both the flood and ebb, and reproduces the ebb dominant flow regime, with peak ebb currents speeds almost twice of those recorded on the flood. Flood speeds are reproduced very well although the spring – neap cycle, although there is a slight underestimation of the peak ebb current speeds. Flow directions on the flood are also reproduced well, whilst there is a small offset of around 5° on the ebb. During the calibration process a number of simulations were undertaken to examine the differences predicted of the ebb, but further improvement was not possible without significantly effecting the model elsewhere. Whilst the Nordic AWAC deployment lies in an area where the bed is relatively stable, changes to the local bathymetry do occur, and the small differences observed could be attributed to localised changes between the model bathymetry used in the model and that at the time the measurements were made.

2.8.7 A review of the calibration metrics (Table 4) show that the model reproduces the measured flows well at AWAC 1, with all metrics within target.

**Table 4. Statistics comparing modelled and measured flows during calibration period**

| Location | Mean Speed Difference (m/s) and (%) | | Mean Direction Difference (°) | | Time Adjusted Fit (Minutes) | RMS Difference (m/s) |
|---|---|---|---|---|---|---|
| | Peak Flood | Peak Ebb | Peak Flood | Peak Ebb | | |
| ***Target*** | *±0.2 m/s (or ±20%)* | | *±10º* | | *±25 minutes* | *0.1 m/s for LEMSA A 0.2 m/s for LEMSA B* |
| AWAC 1 | 0.00 (0%) | -0.17 (-10%) | -6 | -2 | 12 | 0.10 |

## 2.9 Model validation

### Water Levels

2.9.1 The model has been validated against water levels at AWAC 2, the Immingham NTSLF gauge data, and the Admiralty tidal predictions for the spring-neap tidal period (30/08/20 – 09/09/20). Levels have been analysed both visually and statistically following the guidelines outlined in Section 2.7.

2.9.2 A quantitative statistical analysis of water levels at each of the locations is presented in Table 3, with visual comparisons provided in Figure 13 to Figure 18. The visual comparison shows that the general shape and phasing of the tide is reproduced well. However, tidal range is generally underpredicted by the model at each of the locations. From Figure 13 to Figure 18, the tidal range increases as the tide propagates up through the estuary and this increase is also reproduced well by the model.

2.9.3 A review of the calibration metrics show that the model reproduces the measured water levels well through the estuary. Although high and low water levels are not reproduced with absolute measure of ± 0.1 m, the tidal range in the Humber is significant and therefore it is more appropriate to consider these metrics relative to the tidal range, which is achieved well at all sites.

2.9.4 A review of the validation metrics (Table 5) show that the model reproduces the measured water levels well through the estuary over the validation period. Although high and low water levels are not reproduced with absolute measure of ±0.1 m at all of the sites, the tidal range in the Humber is significant and therefore it is more appropriate to consider these metrics relative to the tidal range, which is achieved well at all sites.

2.9.5 The time-adjusted fit values and the RMSE Surface Elevation difference at all locations are again within or extremely close to the target metrics.

**Table 5. Water level validation statistics**

| Location (Calibration data source) | High Water Level Difference in m (and as % of Range) | Low Water Level Difference in m (and as % of Range) | Time Adjusted Fit (mins) | RMSE Surface Elevation Difference (m) |
|---|---|---|---|---|
| *Target* | *± 0.1 m (or to within 10% and 15% of spring and neap tidal ranges)* | *± 0.1 m (or to within 10% and 15% of spring and neap tidal ranges)* | *± 15 to 25 minutes* | *within 0.25 m* |
| AWAC 2 | -0.36 (-7%) | 0.07 (1%) | 15 | 0.26 |
| Spurn Head (TT) | -0.28 (-6%) | 0.07 (2%) | 16 | 0.22 |
| Grimsby (TT) | -0.28 (-6%) | 0.05 (1%) | 11 | 0.21 |
| Immingham (NTSLF) | -0.21 (-4%) | 0.08 (2%) | 7 | 0.18 |
| Hull King George Dock (TT) | -0.31 (-6%) | 0.29 (5%) | 9 | 0.23 |
| Hull Albert Dock (TT) | -0.28 (-5%) | 0.24 (5%) | 13 | 0.23 |
| Note: Where guidance values are exceeded values are shown in Red. | | | | |

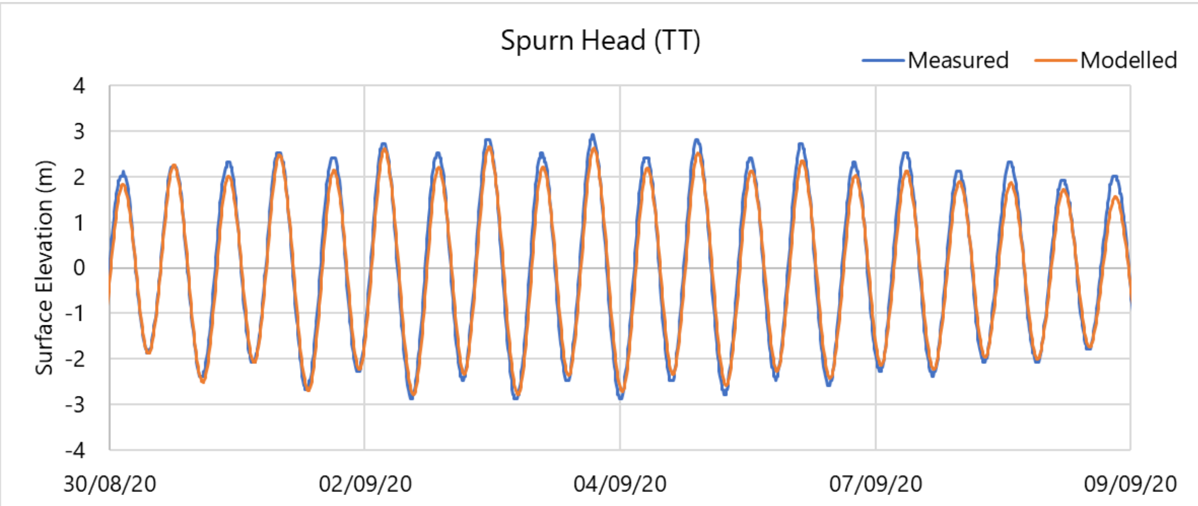


**Figure 13. Comparison of water levels against Admiralty tidal predictions at Spurn Head**

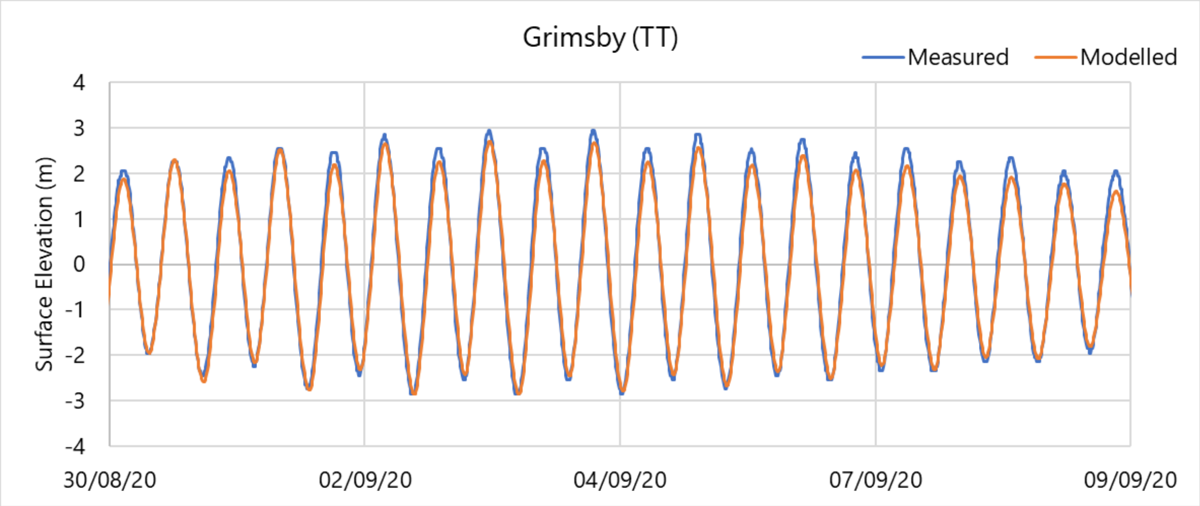


**Figure 14. Comparison of water levels against Admiralty tidal predictions at Grimsby**

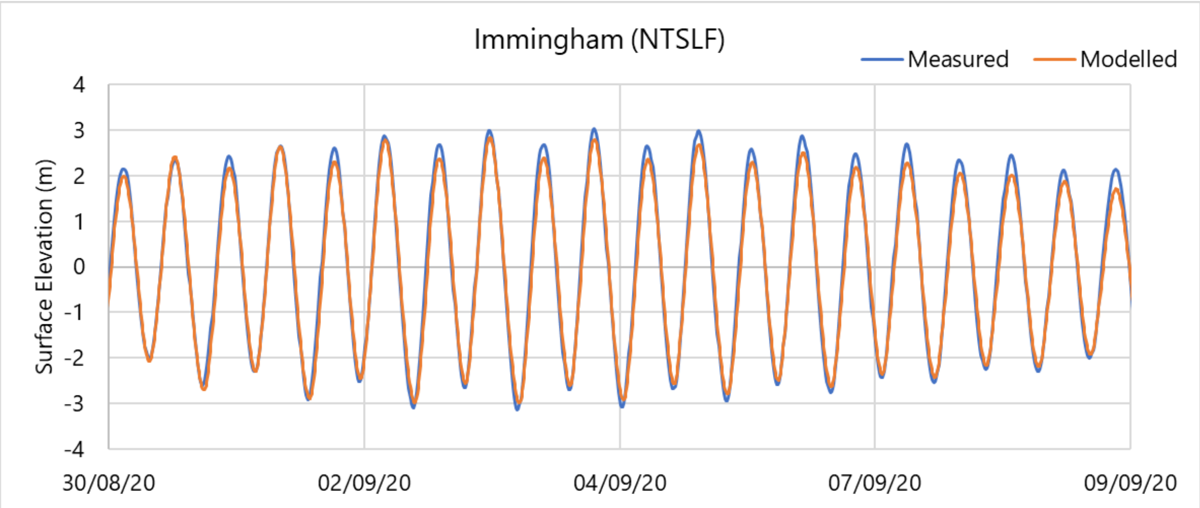


**Figure 15. Comparison of water levels at Immingham**

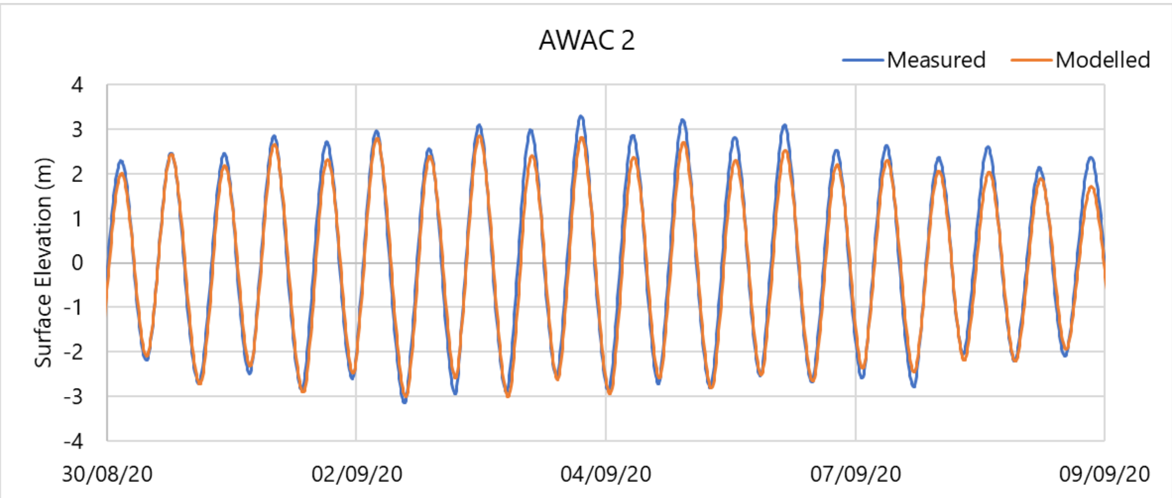


**Figure 16. Comparison of water levels at the Magenta AWAC deployment location (Humber International Terminal)**

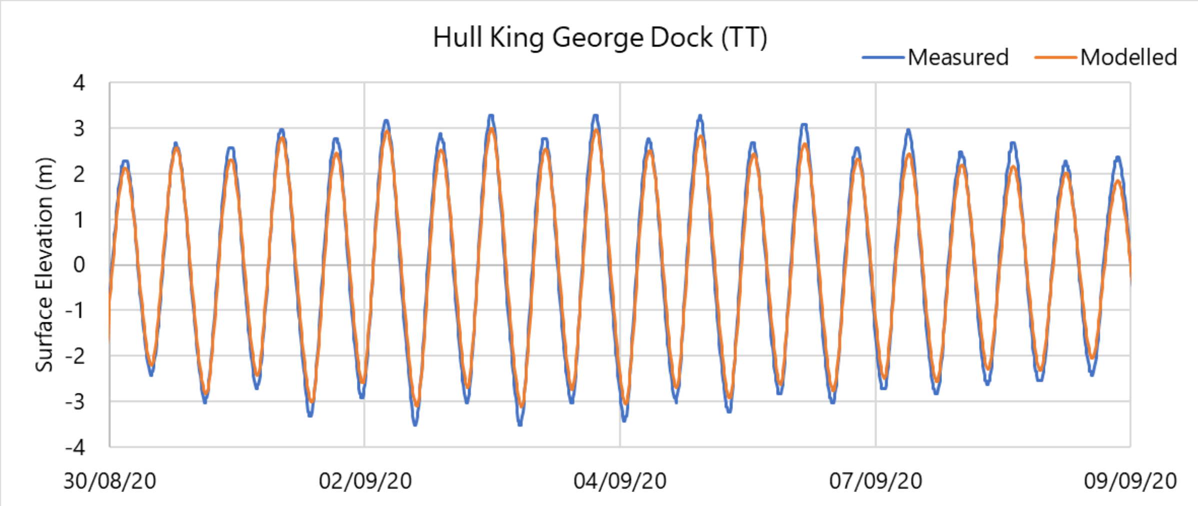


**Figure 17. Comparison of water levels against Admiralty tidal predictions at Hull King George Dock**

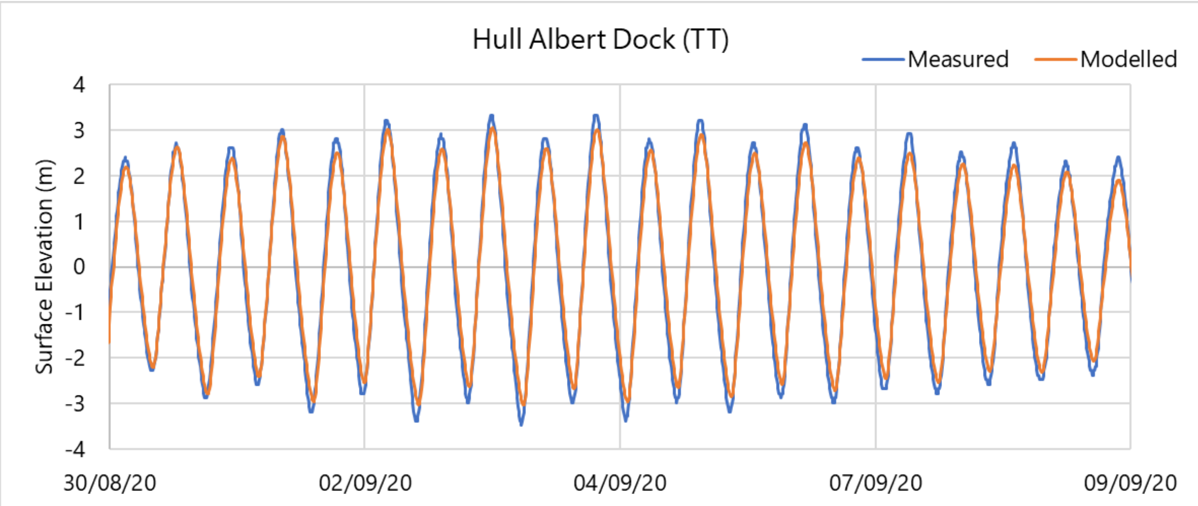


**Figure 18. Comparison of water levels against Admiralty tidal predictions at Hull Albert Dock**

## Currents

2.9.6 The model shows good agreement with the phasing of the flow on both the flood and ebb (Figure 19). Unlike at the Nordic AWAC location, there is less dominance in the ebb flow compared to the flood, although ebb speeds are still slightly faster than the flood. In general, flow speeds are reproduced well through all phases of the tide, however, spikes routinely occur within the measured data around peak ebb that are not reproduced in the model. It is important to note that the instrument was deployed mounted on a seabed frame at a location immediately off Berth 2 of HIT. It is expected that the 'spiky' behaviour of the flow around peak flows is related to very localised accelerations of the flow introduced by the proximity of the instrument to the jetty piles, and any associated bathymetric features such as scour channels.

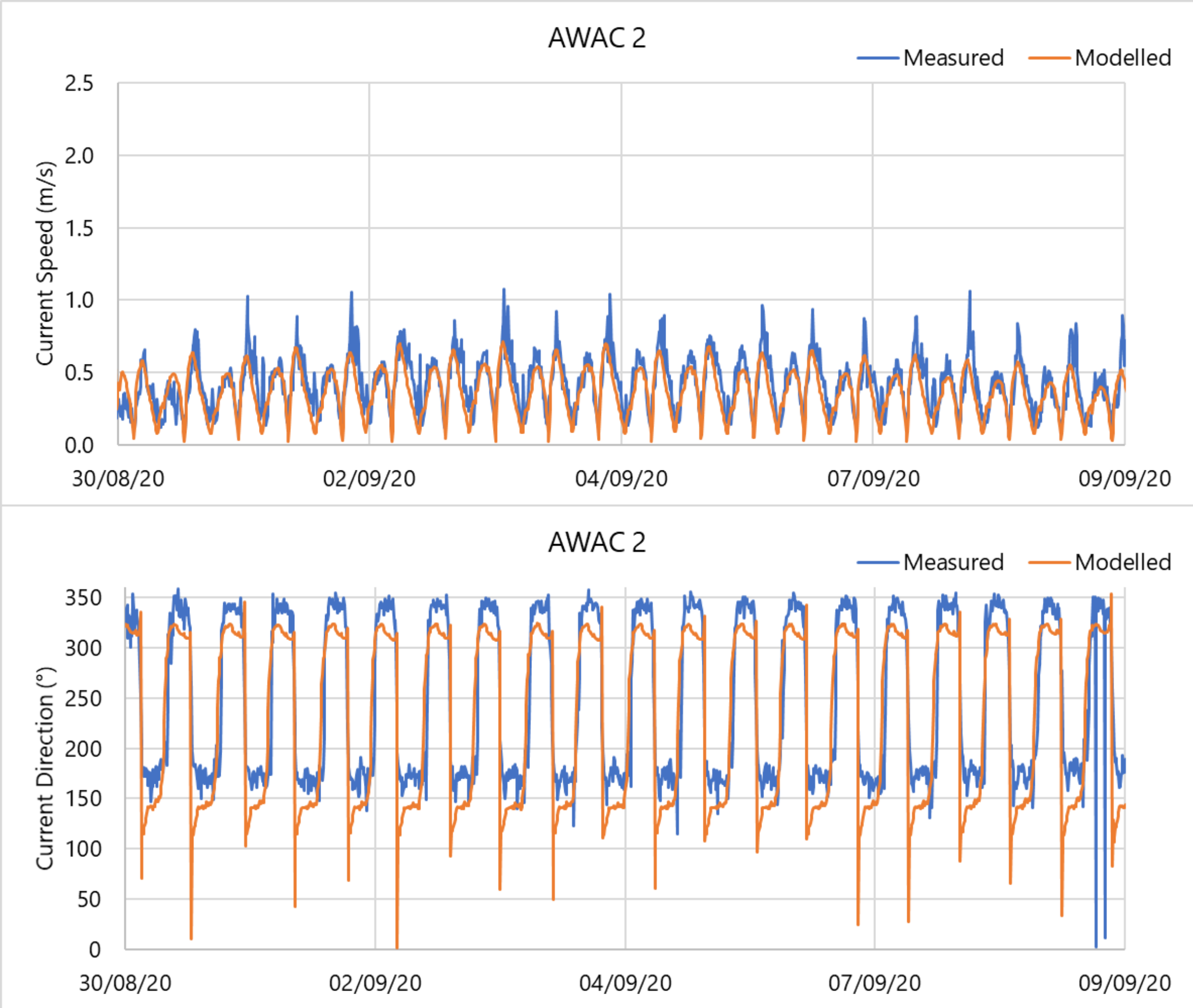


**Figure 19. Comparison of flow speed and direction at the Magenta AWAC deployment location (Humber International Terminal)**

2.9.7 The predicted flow directions are also consistently out by approximately 20º on both the flood an ebb tide and it is expected that this again is feature of the proximity of the instrument to the jetty and any associated localised bathymetric features.

2.9.8 A review of the validation metrics (Table 6) show that the model is underpredicting peak flows on both flood and ebb tide. On the flood tide, the model is within the targets with regards to mean difference in magnitude, however, exceeds the target in terms of percentage.

2.9.9 Flow directions are shown to be out by 12% on the flood (only slightly out of target values), and 25% on the ebb, although the location of the measurement data (located directly off the upstream end of the HIT jetty (and pile) structure. Consequently, it is likely that the adjacent infrastructure is affecting the measured data, particularly with regards to flow directions.

2.9.10 Time adjusted fit is well within the target metrics, as is the RMS difference, which fits targets required for LEMSA B.

**Table 6. Statistics comparing modelled and measured flows during validation period**

| Location | Mean Speed Difference (m/s) and (%) | | Mean Direction Difference (°) | | Time Adjusted Fit (Minutes) | RMS Difference (m/s) |
|---|---|---|---|---|---|---|
| | Peak Flood | Peak Ebb | Peak Flood | Peak Ebb | | |
| ***Target*** | *±0.2 m/s (or ±20%)* | | *±10°* | | *±25 minutes* | *0.1 m/s for LEMSA A 0.2 m/s for LEMSA B* |
| AWAC 2 | -0.08 (-28%) | -0.27 (-36%) | -12 | -25 | -8 | 0.12 |
| Note: Where guidance values are exceeded values are shown in Red | | | | | | |

## 2.10 Summary of hydrodynamic model performance

2.10.1 The numerical hydrodynamic model has been set up, calibrated and validated as described above. Water levels throughout the Humber Estuary are replicated well within the model, particularly when comparing against the target metrics for high water (HW) and low water (LW) bias and the associated time-adjusted fit. Comparisons against the measured flows show the model is also good at representing the peak magnitudes and flow directions. The shape of the tidal wave as it propagates up through the estuary is also well represented in the model.

2.10.2 Overall, the model is considered to be performing well and is able to replicate the hydrodynamic regime across the study area with sufficient precision. The hydrodynamic modelling is considered suitable for use in assessing the predicted impact of the Ro-Ro facility on water levels and flows within the Humber Estuary. The hydrodynamic model is also considered to provide an appropriate basis to examine the sediment transport regime within the estuary (Section 3) and to examine the dispersion of material released from the associated dredging operations (Section 3.4.9).

# 3 Sediment Transport Model

## 3.1 Introduction

3.1.1 The study also aims to assess the potential impact on sediment transport processes, as a result of the proposed Project. This assessment will be built around existing knowledge of the Humber system and informed by bespoke numerical modelling of the baseline and scheme scenarios. To achieve this, the DHI MIKE Mud transport (MT) module has been applied, driven by the outputs from the hydrodynamic modelling described above.

3.1.2 The following sections describe the set up and verification of this transport module.

## 3.2 Mud transport (MT) module setup

3.2.1 The MT module is driven by the outputs from the HD modelling; as such, the model extent, mesh, bathymetry, bed roughness and HD boundary conditions are as described in the previous sections.

### Sediment parameters

3.2.2 Grab sampling data from the project survey campaign (ABPmer, 2020) has been analysed for particle size distribution (Table 7 and Figure 20), and the average composition of the bed material across the proposed Project area (primarily sandy Mud) has defined the sediment grading used within the MT model.

**Table 7. Particle size distribution across the site**

| Sample | Percentage Composition (%) | | | Sediment Description* |
|---|---|---|---|---|
| | Mud | Sand | Gravel | |
| 1 | 90.7 | 9.3 | 0.0 | Mud |
| 2 | 87.5 | 12.5 | 0.0 | Sandy Mud |
| 3 | 77.5 | 22.5 | 0.0 | Sandy Mud |
| 4 | 77.3 | 22.7 | 0.0 | Sandy Mud |
| 5 | 74.0 | 26.0 | 0.0 | Sandy Mud |
| 6 | 80.8 | 19.2 | 0.0 | Sandy Mud |
| 7 | 80.3 | 19.7 | 0.0 | Sandy Mud |
| 8 | 69.7 | 30.3 | 0.0 | Sandy Mud |
| 9 | 80.4 | 19.6 | 0.0 | Sandy Mud |
| 10 | 80.0 | 20.0 | 0.0 | Sandy Mud |
| 11 | 91.0 | 9.0 | 0.0 | Mud |
| 12 | 82.5 | 17.5 | 0.0 | Sandy Mud |
| 13 | 70.5 | 29.5 | 0.0 | Sandy Mud |
| 14 | 80.5 | 19.5 | 0.0 | Sandy Mud |
| 15 | 84.1 | 15.9 | 0.0 | Sandy Mud |
| 16 | 85.1 | 14.9 | 0.0 | Sandy Mud |

| Sample | Percentage Composition (%) | | | Sediment Description* |
|---|---|---|---|---|
| | Mud | Sand | Gravel | |
| 17 | 86.9 | 13.1 | 0.0 | Sandy Mud |
| 18 | 83.8 | 16.2 | 0.0 | Sandy Mud |
| 19 | 91.1 | 8.9 | 0.0 | Mud |
| 20 | 6.9 | 93.1 | 0.0 | Sand |
| * Sediment description after Folk, 1954 | | | | |

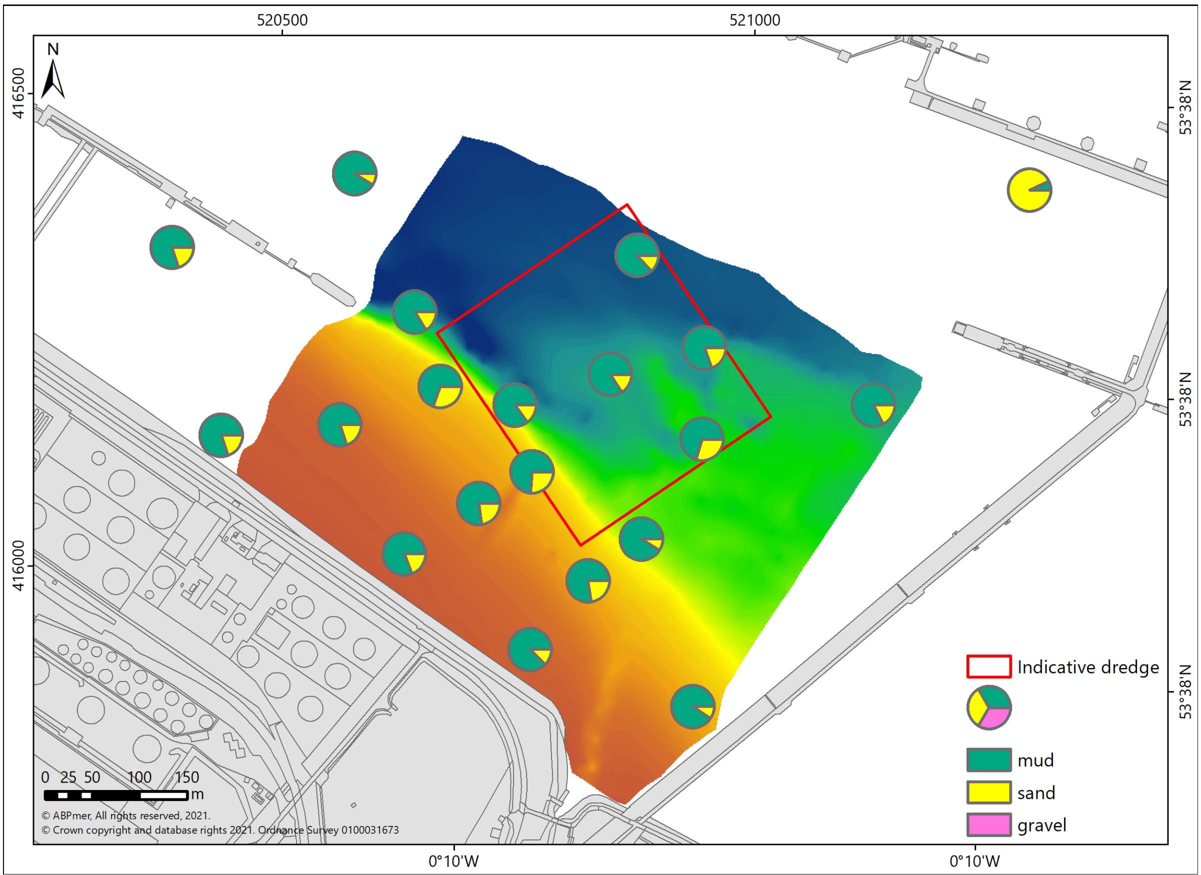


**Figure 20. Particle size distribution across development site**

3.2.3 Table 8 shows the range of model setup parameters (calculated using industry-standard formulae, for example, from van Rijn, 1993), which have been adjusted through the model verification exercise (see following section).

3.2.4 The model bed is comprised of two defined layers: a ‘soft’ layer that material initially settles to, which is relatively low density and more easily re-eroded; and a ‘harder’ lower layer that defines a slightly more consolidated bed. The lower layer is initially defined by a constant thickness of 0.1 m, whilst the upper layer uses a spatially varying thickness, based on known areas of muddy sediment across the study area. This varying thickness map is shown in Figure 21.

**Table 8. MT module - Sediment input parameters**

| Input Parameter | Description |
|---|---|
| Settling parameters (mg/l):<br>Concentration for flocculation<br>Concentration for hindered settling | <br>500<br>1,600 |
| Critical shear stress for deposition (N/m²) | 0.10 |
| Critical shear stress for erosion (N/m²):<br>Layer 1<br>Layer 2 | <br>0.53<br>0.90 |
| Initial Suspended Sediment Concentration (SSC) (mg/l) | 100 |
| Initial bed thickness (m):<br>Layer 1<br>Layer 2 | <br>Variable (see Figure 21)<br>0.10 |
| Boundary inputs (mg/l) | 20 |

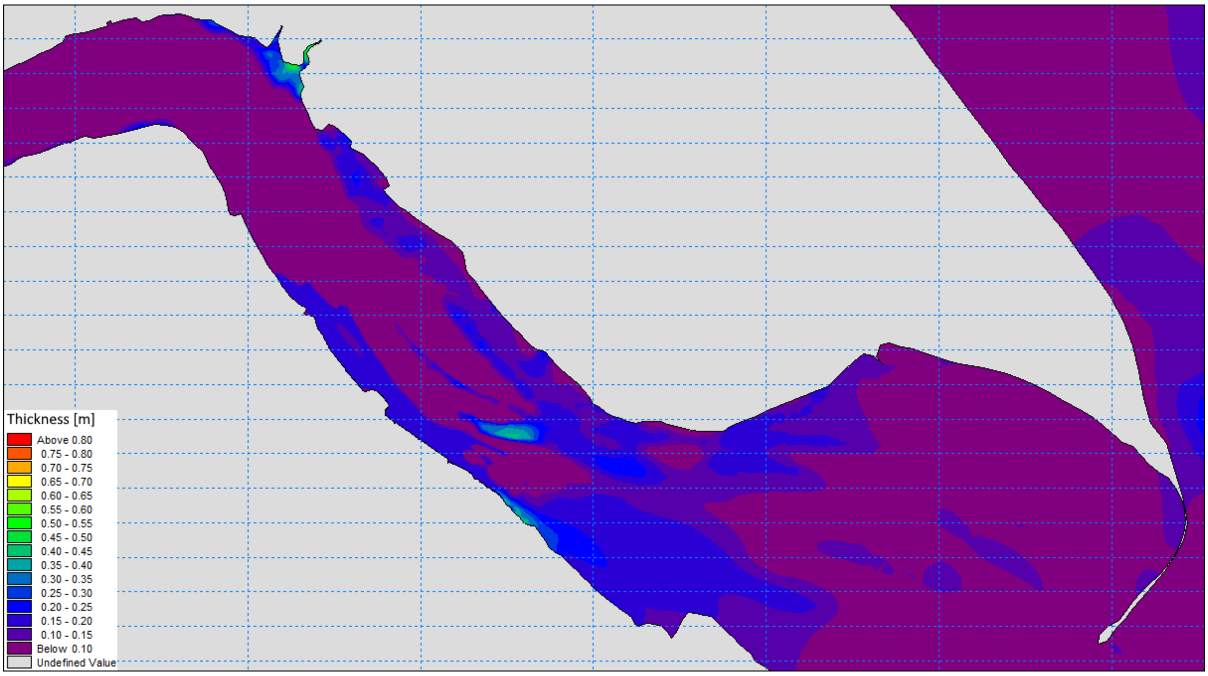


**Figure 21. Spatially varying thickness map for the initial upper bed layer**

## 3.3 Verification data

3.3.1 Dredge load information for the local Immingham berths and dock entrances has been assessed, alongside previous studies on historic bed level change (e.g. ABP R&C, 1995), to consider the typical accretion rates in known parts of the local study area. Data for these areas covers the period from 2004 to 2020 and have then been used to 'train' the baseline MT model run to provide representative levels of bed thickness change. In this way, whilst a 'formal calibration process (in the same way as described above for the hydrodynamic model) is typically not undertaken with sediment transport modelling, the model can be considered to be 'verified' against real-world data. Table 9 shows the typical accretion rates from the available baseline data.

**Table 9. Typical accretion rates in the vicinity of the study area**

| Location | Accretion Rate (m/yr)* | | |
|---|---|---|---|
| | Minimum | Maximum | Average |
| Immingham Outer Harbour (IOH) | 3.5 | 11.9 | 7.2 |
| West Jetty Extension | 0.1 | 2.8 | 0.5 |
| Immingham Gas Terminal (IGT) | 0.6 | 3.5 | 1.0 |
| Immingham Bellmouth | 1.4 | 3.5 | 2.3 |
| Humber International Terminal (HIT) | 1.8 | 7.2 | 3.7 |

* Accretion rates defined by reported dredge load information and based on an assumed bed density of 1,300 kg/m³

3.3.2 In addition to the accretion rates modelled timeseries of suspended sediment concentration (SSC) have been compared against measurements from the project survey deployment. This process provides a further measure of model performance, allowing for consideration of suspended (as well as bedload) transport processes. The measured SSC data shows evidence of some peak concentrations that are likely a result of the deployment setup. Hence, the comparison of the modelled values focusses on the general trend (in measured data) across a mean spring neap tidal cycle.

## 3.4 Model performance

3.4.1 The MT model has been set up as described above, and a range of input parameters adjusted in order to achieve a suitable representation of the baseline accretion rate in the dock entrances in the vicinity of the proposed scheme.

3.4.2 A key consideration in determining the depth of any bed accretion is the *in situ* density of the deposited material. Bed densities can be expected to vary from site to site and, hence, the thickness of any accretion will vary also (for a given mass of sediment). A lower density will result in a greater volume, hence a thicker accretion. In contrast, a higher density will contain the sediment mass in a smaller volume, hence bed thickness will be lower.

3.4.3 Figure 22 shows the modelled baseline accretion across a mean spring neap cycle. This shows the general siltation across the existing dredged berths (which are included in the model baseline as dredged berth pockets), including HIT, Immingham Outer Harbour (IOH), east and west jetties and Immingham Bellmouth. Within the proposed Immingham Eastern Ro-Ro Terminal dredge pocket, the baseline model indicates a generally stable bed with only small levels of siltation (around 0.02 m) along a thin strip of the shallow subtidal.

3.4.4 Analysing the outputs from the baseline spring neap modelled period (Figure 22) and applying a linear scaling factor to cover an annual period, Table 10 shows the modelled accretion rates in the dock entrances, for an *in situ* bed density of 1,300 kg/m³. This table also compares the modelled rates against those calculated from the range of dredged volumes provided in the verification data (and as summarised in Table 9).

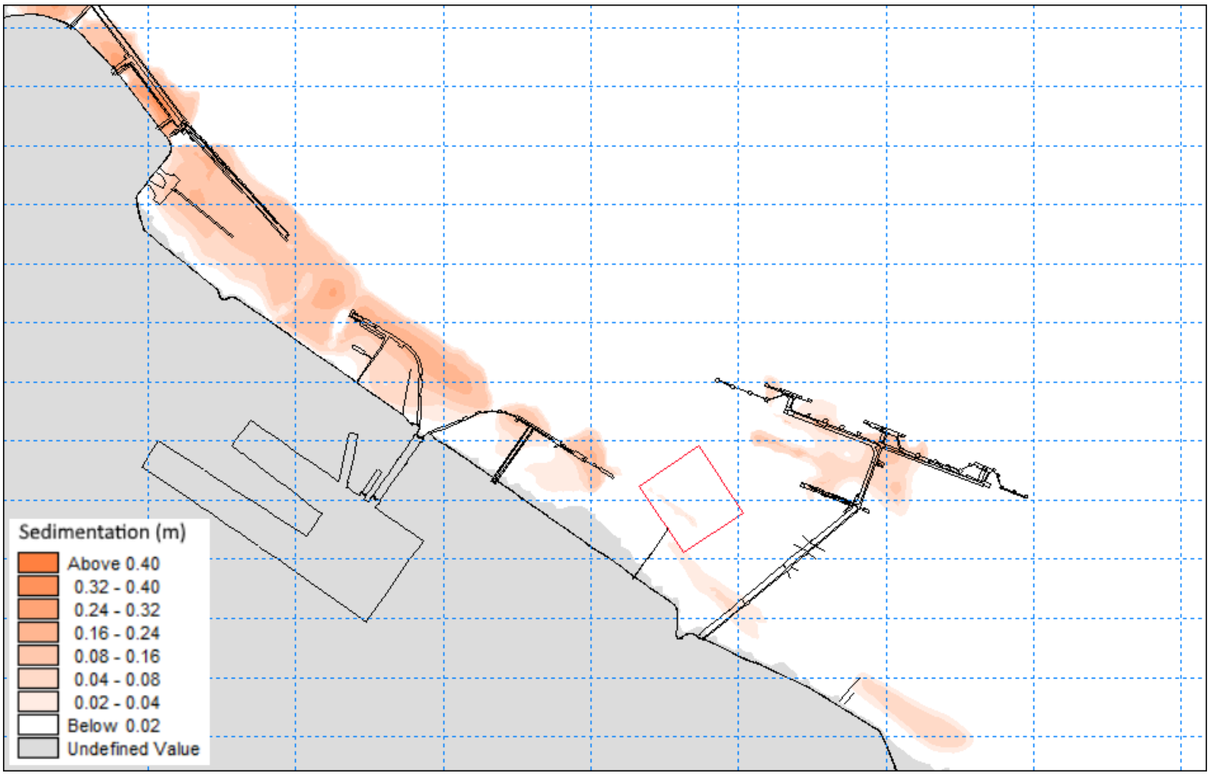


**Figure 22. Baseline sedimentation over a mean spring neap cycle**

**Table 10. Comparison of modelled accretion rates along Immingham frontage**

| Location | Comparison of Accretion Rate (m/yr) | |
|---|---|---|
| | Average Rate From Dredge Load Data | Modelled Rate From MT Module |
| Immingham Outer Harbour (IOH) | 7.2 | 3.9 |
| West Jetty Extension | 0.5 | 0.5 |
| Immingham Gas Terminal (IGT) | 1.0 | 0.8 |
| Immingham Bellmouth | 2.3 | 1.8 |
| Humber International Terminal (HIT) | 3.7 | 2.6 |

3.4.5 The rates from the model compare very well with those defined from the dredging records and analysis of bed level change (Table 9). The majority of locations are very close to the average value derived from the dredge load data, whilst the modelled rate at all locations is within the minimum/maximum envelope exhibited by the data. Small variations to assumed bed density will also influence these predicted accretion rates. Moreover, the general pattern of relative accretion rates in the dredge load data is matched by the model, with IOH showing the largest predicted accretion and the West Jetty Extension the smallest.

3.4.6 Alongside comparison of the modelled deposition values against the dredge load data, predicted SSC values have also been compared against measured values from the survey deployment at the proposed development site (ABPmer, 2020).

3.4.7 This shows that the model is in generally good agreement with the overall trend across the mean spring neap tidal cycle. The variance in peak values between spring and neap tides is well replicated by the model, as are the general peak concentrations, which coincide with the times of peak ebb and flood flows.

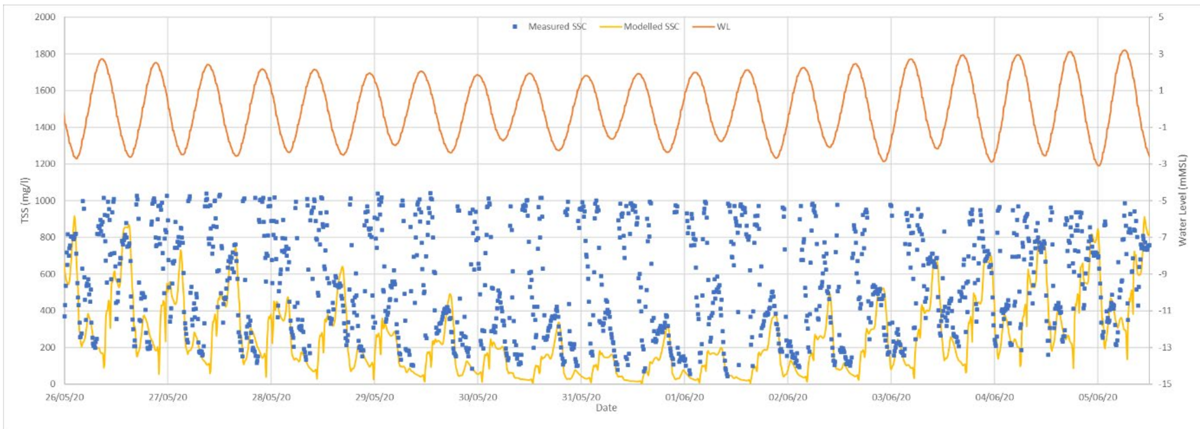


**Figure 23. Comparison of modelled and measured SSC**

3.4.8 Overall, the MT model is performing well, and is considered suitable for use in investigating the potential impacts on mud transport as a result of the proposed scheme.

# 4 Dredging Operations Dispersion Model

## 4.1 Introduction

4.1.1 The potential fate of dredge arisings and spoil from removal to licenced disposal sites has been assessed using the DHI MIKE Particle Tracking (PT) module, driven by outputs from the hydrodynamic model (as described above). The model setup has been informed through the verification of the accompanying mud transport module (see above), with the subsequent assessment using the dredge volumes from the project engineers understanding of the likely dredging process and of the availability of open disposal sites.

## 4.2 Particle Tracking (PT) module setup

4.2.1 As with the MT module (above), the PT module has also been run using the outputs of the calibrated hydrodynamic model (Section 2) to drive the plume dispersion assessment. The composition of the dredged material (and that of the subsequent disposal) has been informed by the sediment sample analysis, carried out for the project (ABPmer, 2020). Table 11 provides the derived composition information used in the plume dispersal modelling.

4.2.2 A range of scenarios have been developed and examined, which have simulated a range of dredge and disposal operations over a number of tidal conditions (spring, neap, flood, ebb). Details of the scenarios examined are provided within the Physical Processes PIER Chapter.

**Table 11. Plume dispersion module - Sediment properties**

| Sediment Description | Grain Diameter (µm) | Settling Velocity (m/s) | Percentage Bed Composition (%) |
|---|---|---|---|
| Fine sand | 100 | $6 \times 10^{-3}$ | 21 |
| Coarse silt | 22 | $3 \times 10^{-4}$ | 57 |
| Fine silt | 4 | $1 \times 10^{-5}$ | 22 |

## 4.3 Model performance

4.3.1 No formal verification of the PT model has been undertaken, but provisional test runs were carried out and the results examined to ensure that the numerical modelling tool is behaving as expected.

# 5 Wave Model

## 5.1 Introduction

5.1.1 In order to assess the impact of the Ro-Ro facility on the wave conditions adjacent to the site, a DHI MIKE21 SW model has been constructed. The model has subsequently been used to examine how waves conditions will be affected during extreme and more frequently occurring events.

5.1.2 The model setup (and validation) is described in the following sections.

## 5.2 Model Grid

5.2.1 The model mesh and bathymetry has been developed from the hydrodynamic model described in Section 2. The SW model uses the same model extent offshore and through the lower estuary but is truncated in the upper estuary around the location of the Humber Bridge. This is because the upper estuary has no influence on the wave conditions that are generated at the site and will not be affected by the development.

5.2.2 The model utilises the same bathymetric data as the hydrodynamic model, however, the model mesh has been de-refined slightly around the Ro-Ro facility to provide a minimum spatial resolution of approximately 40 m. This has improved the computational efficiency whilst maintaining the ability of the model to represent the local wave climate.

5.2.3 Figure 24 shows the full extent of the model mesh and resolution at the Ro-Ro facility and surrounding area. The model bathymetry is provided in Figure 25.


**Figure 24. Overall model extent (top), resolution at key area of interest (bottom)**

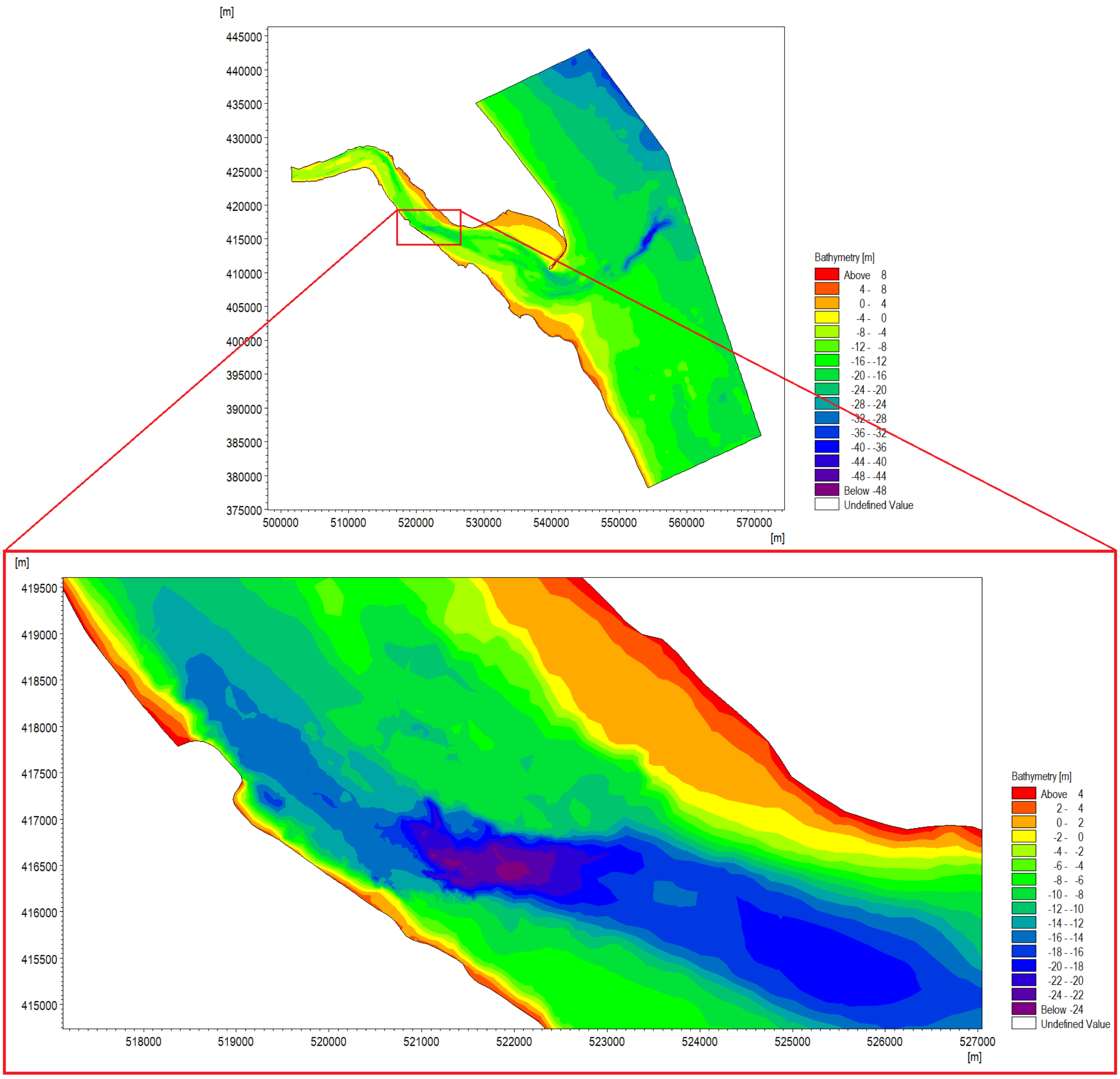


**Figure 25. Overall model bathymetry (top), bathymetry over key area of interest (bottom)**

## 5.3 Model parameters

5.3.1 The primary model parameters are as described below, with the model boundary and forcing conditions described in subsequent sections.

- **Spectral resolution:** The model was run with a logarithmic discretization type, with 22 frequencies, covering periods from 0.47 to 14.9 seconds.
- **Model Bed friction:** The model uses a Nikuradse roughness value of 0.001 m constant over the model domain. This value is significantly lower than the default value of 0.04 m, but from experience is considered to be much more appropriate given the nature of the site.
- **Wave breaking:** Included using default parameters.
- **Wave - Wave interaction**: Included using quadruplet-wave interaction.

- **Currents:** The effect of currents is excluded from the main simulations and is of limited importance at high water when waves at the site will be greatest, although the sensitivity to currents was examined through the verification exercise.
- **Diffraction:** Excluded from model setup and of limited importance over model domain.

## 5.4 Wave model verification

5.4.1 The principle aim of the present assessment is to examine how waves within the Humber and adjacent to the site may be affected by the development, which is to be assessed by examining wave conditions at the site for a number of discrete extreme and more frequent events. Therefore, a more formal calibration/validation exercise has not been undertaken, instead the general performance of the model has been examined by simulating wave conditions at the site, over a short period during which waves were recorded at the site during the Nordic AWAC deployment. The location of the Nordic AWAC deployment is shown in Figure 5.

5.4.2 The period used in this verification exercise covers the 25/05/20 to 05/06/20, during which a number of events were recorded by the Nordic AWAC. For this period, offshore wave conditions were extracted from the ABPmer SEASTATES hindcast wave model of the UK continental shelf. Wave conditions were extracted along the full length of the boundary.

5.4.3 The model was then run with varying waters levels extracted from a hydrodynamic model simulation for the same period (Section 2), both with and without currents included. Associated wind speeds from the National Centers for Environmental Prediction (NCEP) Climate Forecast System v2 (CFSv2) (http://rda.ucar.edu/datasets/ds094.1/) hindcast database were also applied to the model.

5.4.4 The results of this verification simulation (with currents included) are presented in Figure 26. The model provides a good comparison against the measured data. Sensitivity testing has showed that applying variations to water levels and currents in the model has no notable effect on model performance. Discrepancies in the comparison of the wave events evident in the measured data between the 28 and 31 May 2020, are likely a result of other factors that are influencing wave height, such as thermal winds (particularly given the record levels of sunshine experienced over the UK during May 2020), which are not represented in the model.

5.4.5 Overall, the performance of the model is considered sufficient for use in the subsequent assessment of potential impact on defined wave events.

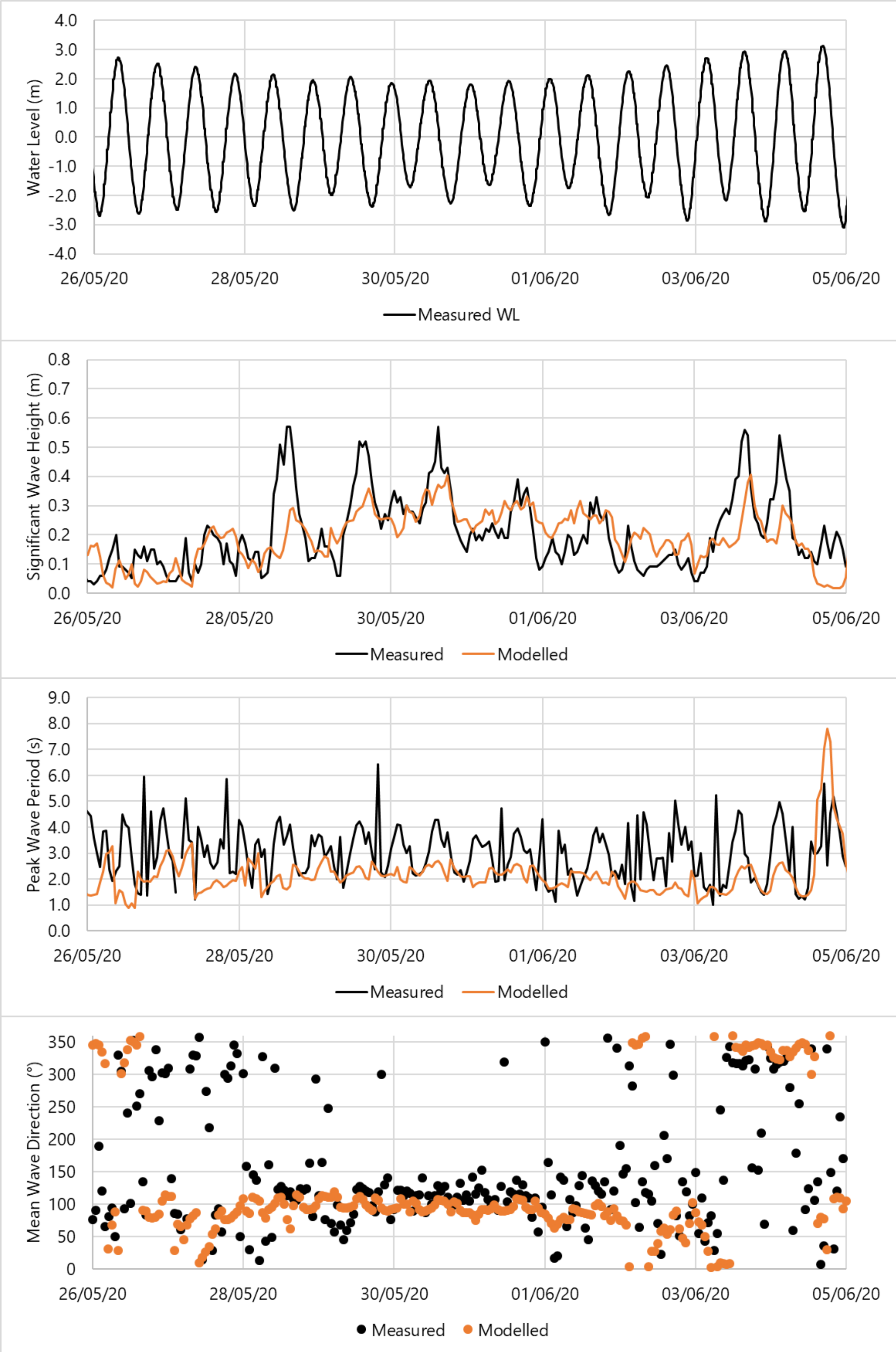


**Figure 26. Comparison of Hs, Tp and mean wave direction at the Nordic AWAC deployment location (Immingham Oil Terminal)**

## 5.5 Derivation of wave Conditions used in impacts assessment

5.5.1 Within the main assessment the effect of the proposed development on wave condition in the Humber and adjacent to the site has been examined for a number of discrete extreme and more frequently occurring events. The derivation of these discrete events is described below.

5.5.2 Long-term hindcast wave data at the model boundary (just offshore of the entrance to the Humber Estuary) have been extracted from the ABPmer SEASTATES hindcast wave model of the UK continental shelf (www.seastates.net). The water depth at the data extraction point is -15.2 mODN.

5.5.3 This SEASTATES hindcast model has been extensively calibrated at locations around the UK coastline, and provides a 41-year hourly hindcast of wave parameters (including height, period and direction), covering the periods 1979 and 2020, inclusive.

5.5.4 The extracted data is presented in Figure 27 and Table 12 as both a wave rose and scatter table of significant wave height vs mean wave direction.

5.5.5 From this data, three directional sectors have been selected from which to derive extreme wave conditions entering the Humber. These are shown in Table 13 and highlighted in Table 12 with coloured shading in the table headers.

5.5.6 A 'central' direction has also been selected for each sector, which will be the direction from which the extreme waves are specified in the model simulations. For the eastern and south eastern sectors this sits in the true centre of the filtered directional bins. For the north east (NE) sector, the larger wave events prevail from more northerly sectors, however, the extreme waves derived from the NE sector have been modelled from a direction of 45° as they will have greater potential for propagating into the estuary. In this way, the modelling approach represents a conservative worst case.

5.5.7 In order to associate a wind condition with each wave event, wind data has also been extracted from the ABPmer SEASTATES model for the same location. These winds are sourced from the NCEP Reanalysis II dataset between 1979 and 2009 and, more recently (2010 to present), from the CFSv2 (http://rda.ucar.edu/datasets/ds094.1/) hindcast database. These are the wind fields used to drive the SEASTATES wave hindcast. The wind speed parameters are considered representative of speeds at 10 m above sea level with a 1-hourly averaging period.

## Table 12. Significant wave height vs. mean wave direction at the Humber boundary location

| Hs (m) | Mean Wave Direction (°from) | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | NE | | | | E | | | SE | | | | | | | | | | | | | | | | |
| | 352.5 - 7.5 | 7.5 - 22.5 | 22.5 - 37.5 | 37.5 - 52.5 | 52.5 - 67.5 | 67.5 - 82.5 | 82.5 - 97.5 | 97.5 - 112.5 | 112.5 - 127.5 | 127.5 - 142.5 | 142.5 - 157.5 | 157.5 - 172.5 | 172.5 - 187.5 | 187.5 - 202.5 | 202.5 - 217.5 | 217.5 - 232.5 | 232.5 - 247.5 | 247.5 - 262.5 | 262.5 - 277.5 | 277.5 - 292.5 | 292.5 - 307.5 | 307.5 - 322.5 | 322.5 - 337.5 | 337.5 - 352.5 | Sum |
| 6.5 - 7 | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 6 - 6.5 | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 5.5 - 6 | | | | | | | | | | | | | | | | | | | | 2 | | | | | 2 |
| 5 - 5.5 | 6 | 3 | 3 | | | | | | | | | | | | | | | | 2 | 1 | | | | | 15 |
| 4.5 - 5 | 18 | 44 | 16 | 4 | 1 | | | | | 1 | 2 | | | | | | 5 | | 6 | 3 | 2 | 1 | 3 | 4 | 110 |
| 4 - 4.5 | 63 | 88 | 36 | 63 | 16 | | | 1 | 4 | 2 | 4 | 9 | 7 | 2 | 2 | 4 | 4 | 8 | 8 | 15 | 12 | 7 | 4 | 23 | 382 |
| 3.5 - 4 | 333 | 246 | 67 | 70 | 62 | 38 | 11 | 12 | | 3 | 10 | 24 | 17 | 1 | 11 | 15 | 10 | 20 | 15 | 33 | 30 | 20 | 30 | 43 | 1121 |
| 3 - 3.5 | 860 | 368 | 137 | 109 | 168 | 178 | 62 | 46 | 18 | 16 | 45 | 60 | 80 | 36 | 29 | 37 | 25 | 44 | 63 | 93 | 140 | 71 | 58 | 134 | 2877 |
| 2.5 - 3 | 1887 | 653 | 348 | 285 | 362 | 415 | 212 | 84 | 87 | 117 | 132 | 237 | 281 | 233 | 170 | 103 | 126 | 134 | 194 | 289 | 384 | 268 | 196 | 342 | 7539 |
| 2 - 2.5 | 3066 | 1191 | 609 | 634 | 610 | 729 | 468 | 318 | 374 | 256 | 349 | 638 | 850 | 1031 | 694 | 439 | 494 | 556 | 588 | 816 | 834 | 568 | 498 | 1109 | 17719 |
| 1.5 - 2 | 6071 | 3057 | 1372 | 1453 | 1379 | 1217 | 1340 | 1086 | 1076 | 895 | 978 | 1443 | 2158 | 2862 | 2619 | 1939 | 1609 | 1575 | 1752 | 1722 | 1569 | 1318 | 1489 | 2920 | 44899 |
| 1 - 1.5 | 11374 | 9863 | 4587 | 3851 | 3597 | 3386 | 3098 | 3052 | 2941 | 2718 | 2478 | 3320 | 4441 | 5462 | 5426 | 4487 | 3491 | 3455 | 3394 | 3607 | 3405 | 3271 | 3791 | 5129 | 103624 |
| 0.5 - 1 | 10262 | 12309 | 8638 | 7655 | 6574 | 6723 | 6578 | 5629 | 5807 | 5372 | 4838 | 5405 | 6918 | 7296 | 7006 | 6380 | 5284 | 5169 | 4995 | 5093 | 4750 | 5314 | 6002 | 7769 | 157766 |
| 0 - 0.5 | 1242 | 849 | 752 | 780 | 926 | 862 | 1047 | 1139 | 1069 | 1033 | 953 | 955 | 1002 | 1174 | 1195 | 1166 | 1134 | 1049 | 882 | 819 | 816 | 737 | 760 | 1005 | 23346 |
| Sum | 35182 | 28671 | 16565 | 14904 | 13695 | 13548 | 12816 | 11367 | 11376 | 10413 | 9789 | 12091 | 15754 | 18097 | 17152 | 14570 | 12182 | 12010 | 11899 | 12493 | 11942 | 11575 | 12831 | 18478 | 359400 |
| Percentage | 9.8% | 8.0% | 4.6% | 4.1% | 3.8% | 3.8% | 3.6% | 3.2% | 3.2% | 2.9% | 2.7% | 3.4% | 4.4% | 5.0% | 4.8% | 4.1% | 3.4% | 3.3% | 3.3% | 3.5% | 3.3% | 3.2% | 3.6% | 5.1% | 100.0% |

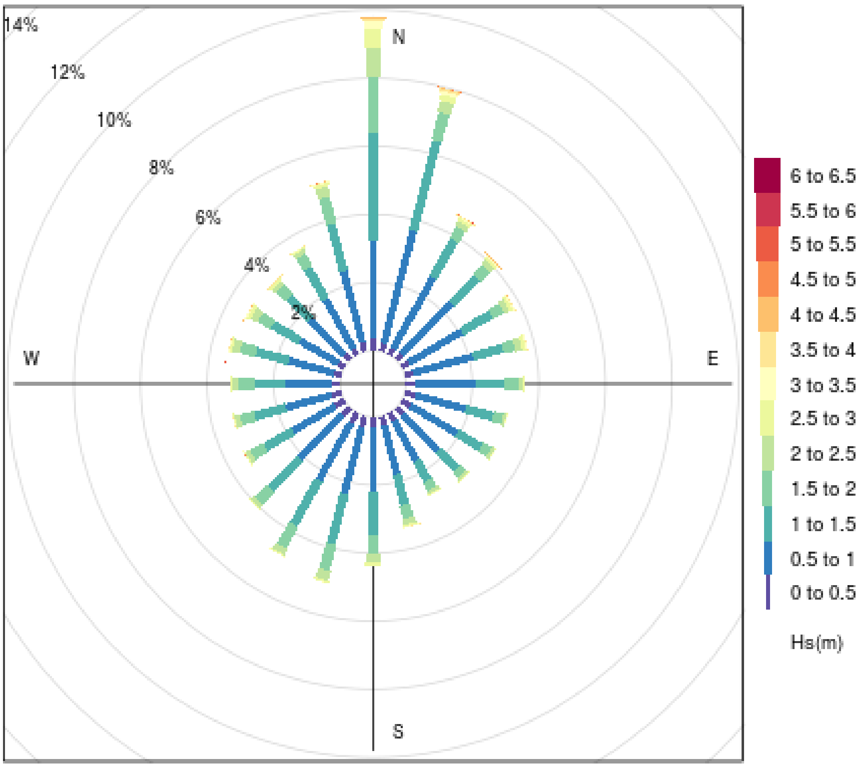


**Figure 27. Wave Rose at Humber Boundary**

**Table 13. Selected directional sectors (degN) for swell waves**

| Selected Sectors | From (°N) | To (°N) | Central Direction for Modelling (°N) |
|---|---|---|---|
| NE | 7.5 | 67.5 | 45 |
| E | 67.5 | 112.5 | 90 |
| SE | 112.5 | 157.5 | 135 |

5.5.8 For the three direction sectors identified, extreme significant wave heights have been derived following the following approach:

- Independent storm peaks have been obtained from the time series of significant wave height. An independent storm peak is defined as having:
  - A minimum of 1-hour duration;
  - A period of at least 24 hours between separate storm events, and;
  - A height above a fixed Hs threshold.
- The selected Hs storm peaks are loaded into the Extreme Value Analysis (EVA) software.
- A Generalised Pareto Distribution (GPD) is fitted to the storm peaks and the shape and scale parameters of the fit determined;
- The Pareto fit to data is visually assessed and, if necessary, the storm peaks are reselected or the threshold varied, and the data refitted to improve the fit quality; and;
- The final shape and scale parameters are used to extrapolate the theoretical fit to data in order to determine extreme return period events.

5.5.9 For each of the directional sectors wave conditions have been derived for:

- 1 in 0.5-year, and
- 1 in 50-year

5.5.10 The resulting wave heights are presented in Table 14 and the Extreme Value Analysis plots associated with these values are provided in Figure 28 to Figure 30.

5.5.11 The spectral peak wave periods (Tp) provided in Table 14, were derived by an asymptotic steepness approximation. In higher sea states the wave steepness tends to become invariant with further increases in wave height. Therefore, estimations of wave steepness from the upper 50 sea states are identified and the 50th percentile of these was used to derive associated wave periods for the extreme significant wave heights. An example of the steepness relationship is shown in Figure 31.

5.5.12 Similarly, the wind conditions presented in Table 14, were determined by deriving a frequency tables of wave height vs. wind speed for each of the directions sectors examined. For each of the extreme wave heights in Table 14 the associated, most frequently occurring, wind speed (to the nearest 2 m/s) was extracted from the frequency table.

**Table 14. Extreme Boundary Wave Conditions for the Humber Spectral Wave Model**

| Return period (yr) | | North-easterly | Easterly | South-easterly |
|---|---|---|---|---|
| | | All Year | All Year | All Year |
| 0.5 | Hs (m) | 3.4 | 2.4 | 2.4 |
| | Tp (s) | 9.0 | 6.7 | 5.6 |
| | WS (m/s) | 15.0 | 13.0 | 15.0 |
| 50 | Hs (m) | 5.2 | 4.1 | 4.8 |
| | Tp (s) | 11.1 | 8.7 | 7.9 |
| | WS (m/s) | 23.0 | 21.0 | 25.0 |

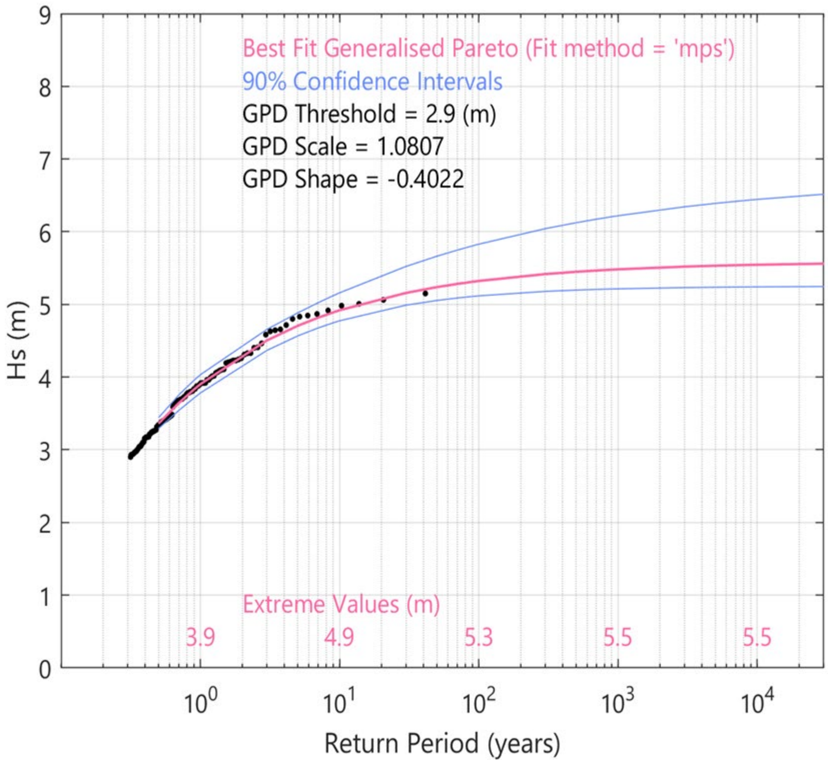


**Figure 28. Extreme Hs GPD fit: Northeast All Year**

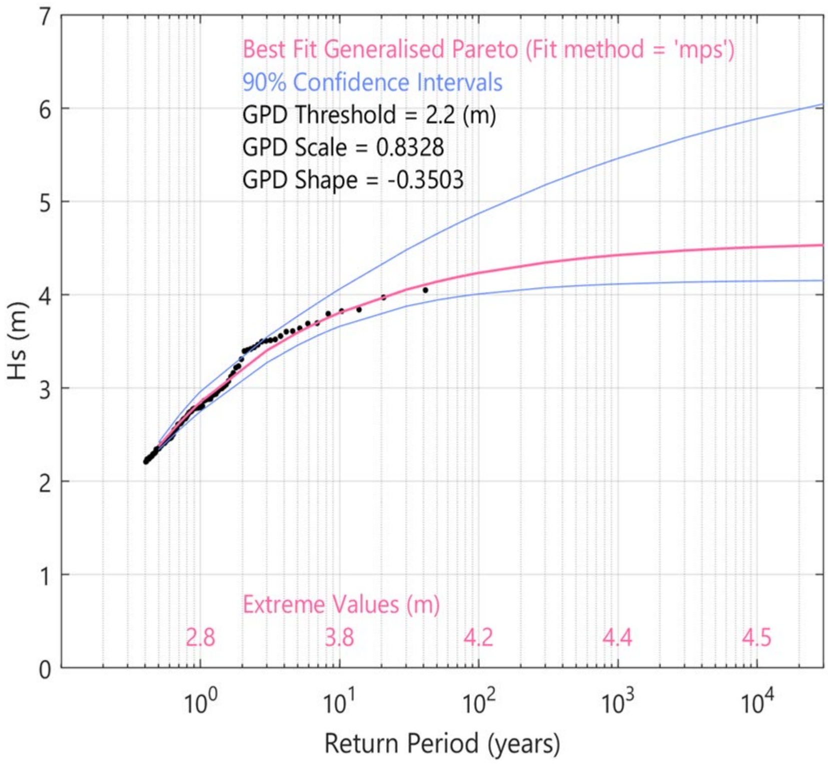


**Figure 29. Extreme Hs GPD fit: East All Year**

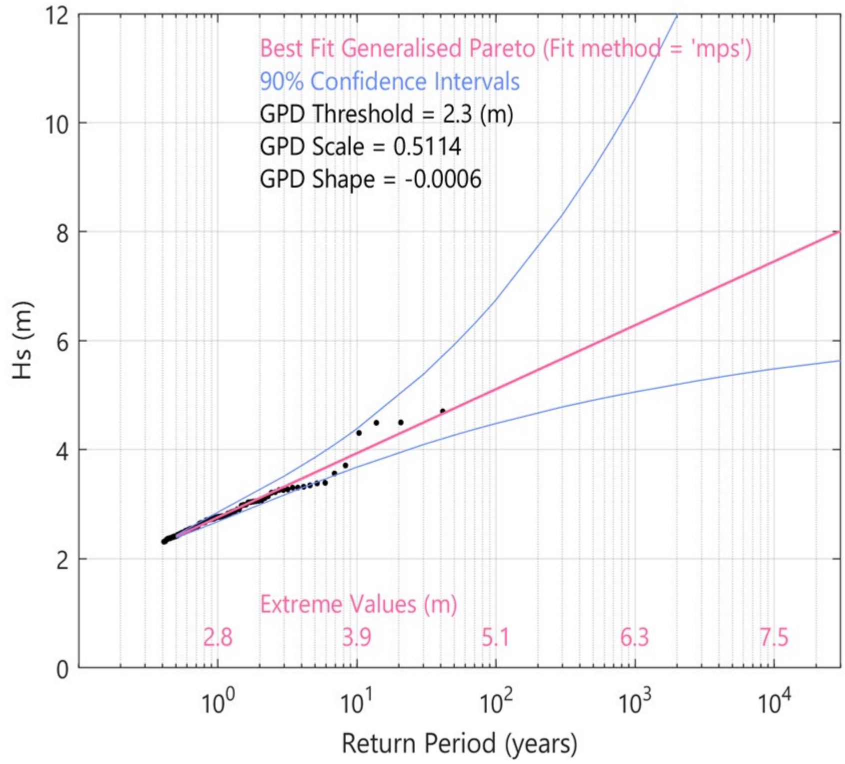


**Figure 30. Extreme Hs GPD fit: Southeast All Year**

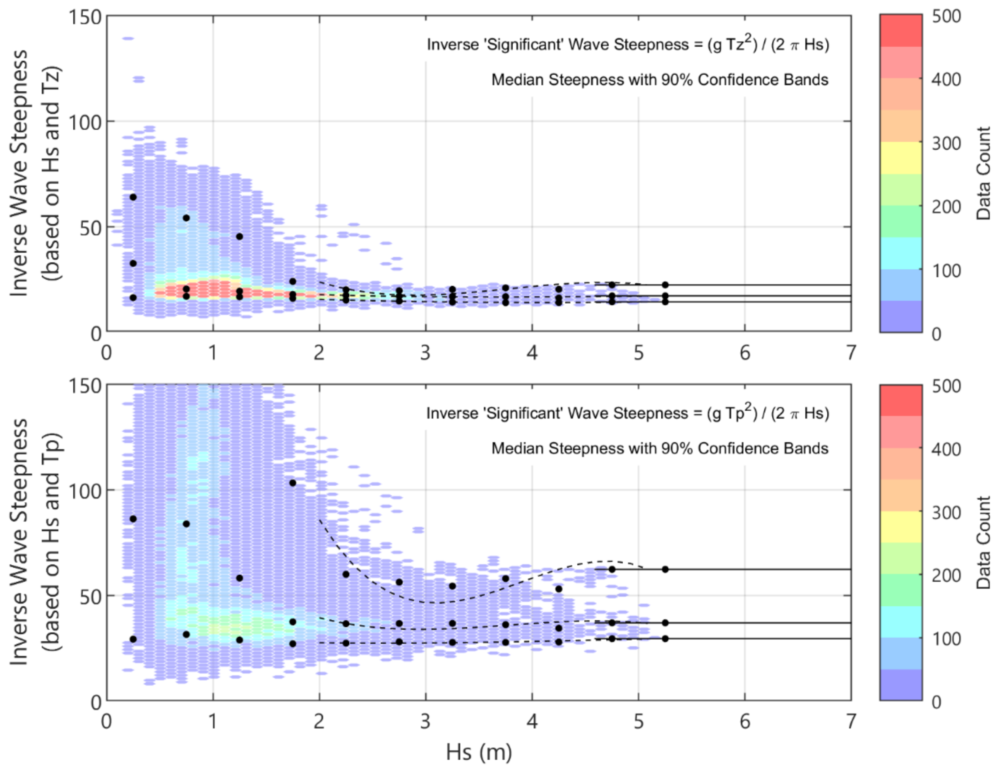


**Figure 31. Asymptotic Wave Steepness: North East Sector, All Year condition**

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# 7 Abbreviations/Acronyms

| Acronym | Definition |
|---|---|
| ABP | Associated British Ports |
| AWAC | Acoustic Wave and Current |
| CFS | Climate Forecast System |
| DHI | Danish Hydraulic Institute |
| E | East |
| EA | Environment Agency |
| EVA | Extreme Value Analysis |
| GPD | Generalised Pareto Distribution |
| HD | Hydrodynamic |
| HIT | Humber International Terminal |
| Hs | Significant Wave Height |
| HW | High Water |
| IGT | Immingham Gas Terminal |
| IOH | Immingham Outer Harbour |
| KGD | King George Dock |
| LW | Low Water |
| MSL | Mean Sea Level |
| MT | Mud Transport |
| NCEP | National Centers for Environmental Prediction |
| NE | North East |
| NTSLF | National Tidal and Sea Level Facility |
| PT | Particle Tracking |
| RMS | Root Mean Square |
| RMSE | Root Mean Square Error |
| SE | South East |
| SSC | Suspended Sediment Concentration |
| SW | Spectral Wave |
| Tp | Spectral Peak Wave Periods |
| TT | Total Tide |
| UK | United Kingdom |
| UKHO | United Kingdom Hydrographic Office |
| WL | Water Level |
| WS | Wave Speed |

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

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