Port of Mostyn

Mostyn Energy Park Extension

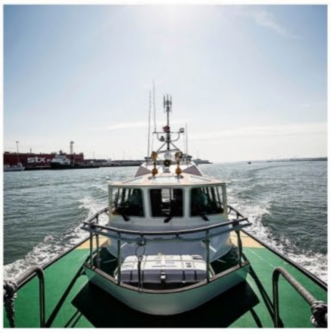
Environmental Statement

Appendix 6.2: Numerical Model Setup and Calibration Report

December 2022







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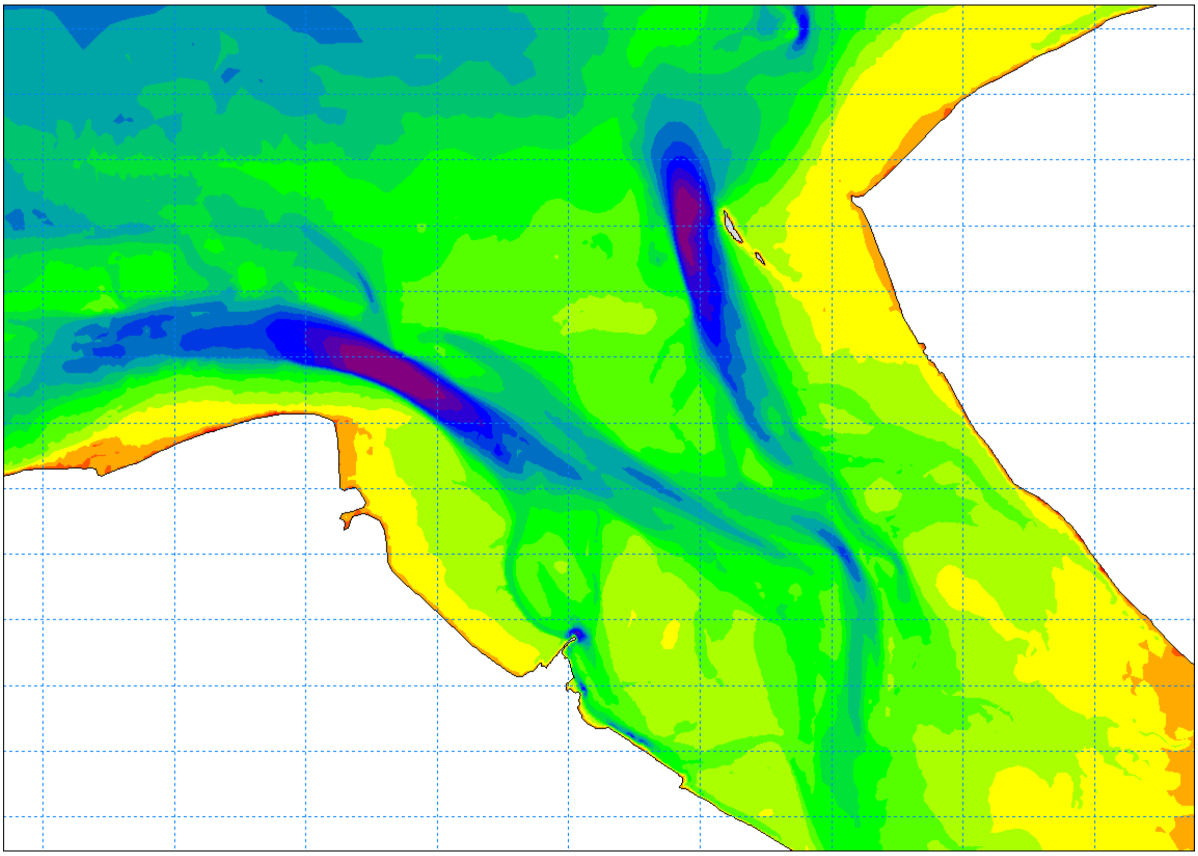

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1 Introduction

The Port of Mostyn on the Dee Estuary, North Wales (Figure 1), is seeking to obtain permission for the construction and operation of the Mostyn Energy Park Extension (MEPE). The location of the proposed scheme is on the up-estuary side of the existing port, as shown in in Figure 1.

To inform the EIA required for the development, a set of numerical modelling tools have been developed to investigate potential impacts on the local and regional hydrodynamic, wave and sediment regime of the study area. This report reviews the work that was undertaken to develop and calibrate these numerical modelling tools.

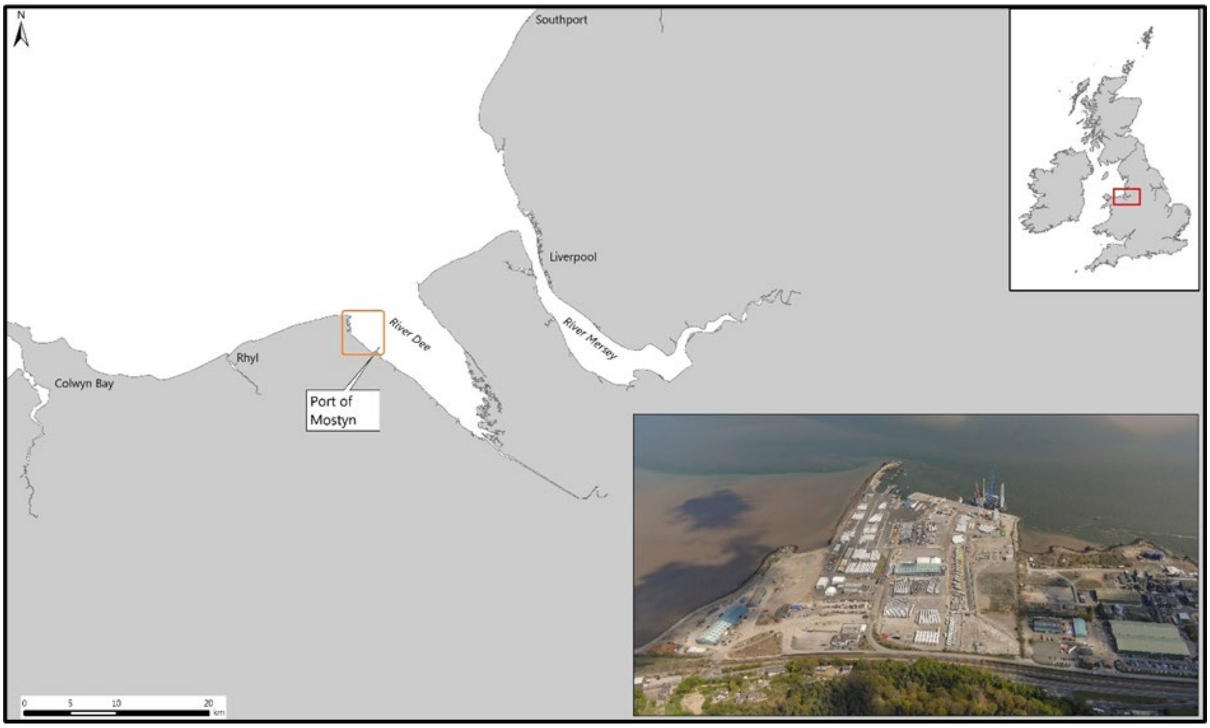


Figure 1. Location of the Port of Mostyn with aerial view of the Port from the south west

For this study, a set of numerical models was built using the Danish Hydraulic Institute (DHI) software package MIKE21 FM (Flexible Mesh). The modelling system was developed by MIKE DHI for complex applications within oceanographic, coastal and estuarine environments. MIKE21 FM is used to simulate the water level variation and two-dimensional (depth averaged) flows in the area of interest. Additional modules of the DHI modelling suite have also been implemented (as necessary), to assess further aspects of the scheme (e.g. dredge plume tracking, sediment transport processes, wave regime).

This report provides a description of the numerical models that have been applied for the MEPE EIA studies. It details the calibration and validation processes undertaken to verify that the models produce a representative simulation of the existing processes. The model outputs have then been used (within the ES) to assess the extent and magnitude of potential physical process effects for the MEPE scheme. It has also informed consideration of effects on other topics (e.g. ecology).

This report documents the modelling methodology and is structured as follows:

- **Section 1**: Introduction;
- **Section 2**: Model Development;
- **Section 3**: Calibration and Validation; and
- **Section 4**: Conclusion and Summary.

2 Model Development

The following sections detail the setup and development of the numerical models created to inform the MEPE EIA studies.

2.1 Mesh design

The Dee Estuary is a semi-enclosed coastal water body open to the Irish Sea through an entrance about 8.2 km wide. The estuary is tidal for about 35 km up-estuary of the entrance on the River Dee (to the weir at Chester). The entrance to the Dee Estuary is characterised by a series of banks and channels, notably Mostyn Bank, Salisbury Middle, West Hoyle Spit, East Hoyle Bank, Welsh Channel, Hilbre Channel and Mid Hoyle Channel (Figure 6). The Welsh, Hilbre and mid-Hoyle channel (as well as relatively fixed points such as Hilbre Island or the Holocene clay bank of the Salisbury Middle) play a key role in influencing tidal exchange between the estuary and coastal waters. The relative contribution that these features make to tidal dynamics in the estuary evidently alters over long-term timescales as their alignments and orientations adjust. In order to encompass the outer banks and Liverpool Bay (which influence the flow dynamics in this region), a large area of the southern Irish Sea was included in the model, extending west to east from Llandudno to Formby and into the Mersey Estuary. The model extends offshore approximately 25 km (Figure 2).

Two open offshore boundaries (described further in Section 2.3.1) were defined, allowing for orientation to the natural flows, either parallel, or perpendicular, to the general offshore flow directions. This approach provides a more accurate simulation of the flow and water level dynamics along the boundaries. In addition to the offshore boundaries, an upstream river boundary has also been included to represent the inflow from the River Dee at Chester Weir.

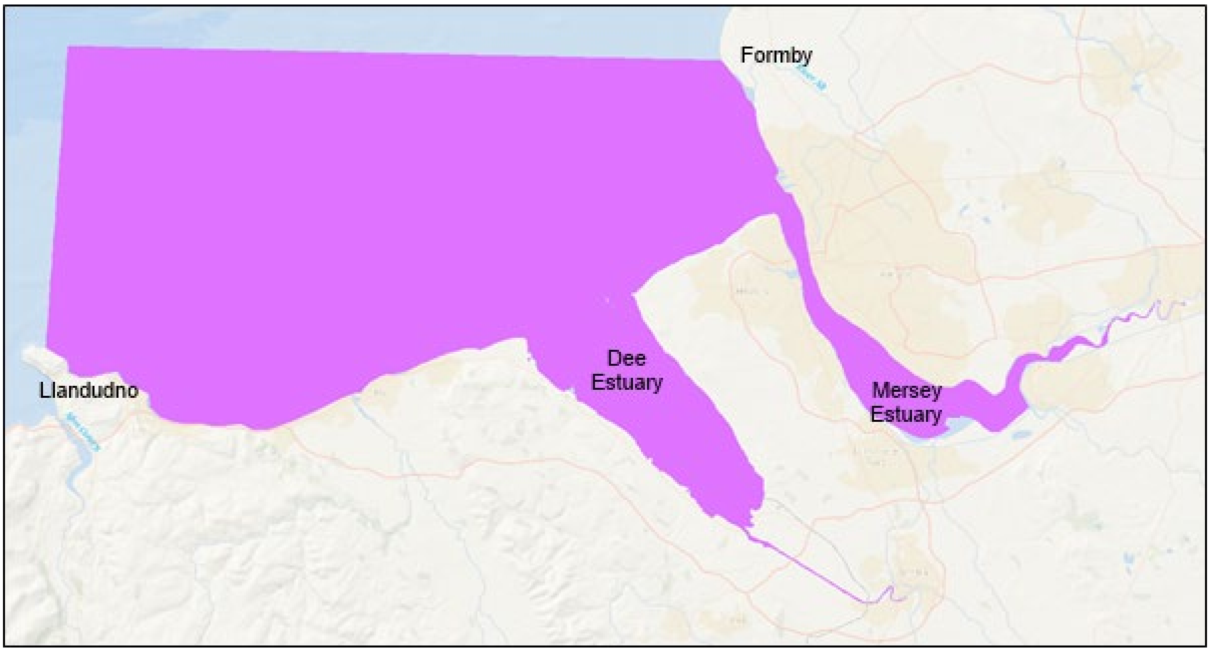


Figure 2. Full hydrodynamic model extent covering southern Irish Sea

Within the MIKE21 software, the HD module can be constructed using either a rectilinear mesh (RM) or flexible mesh (FM) covering the area of interest. For this project, the mesh has been designed by combining the two types; FM is used across the majority of the model extent whilst RM is used in the river sections approximately upstream of Connah's Quay (Figure 3).

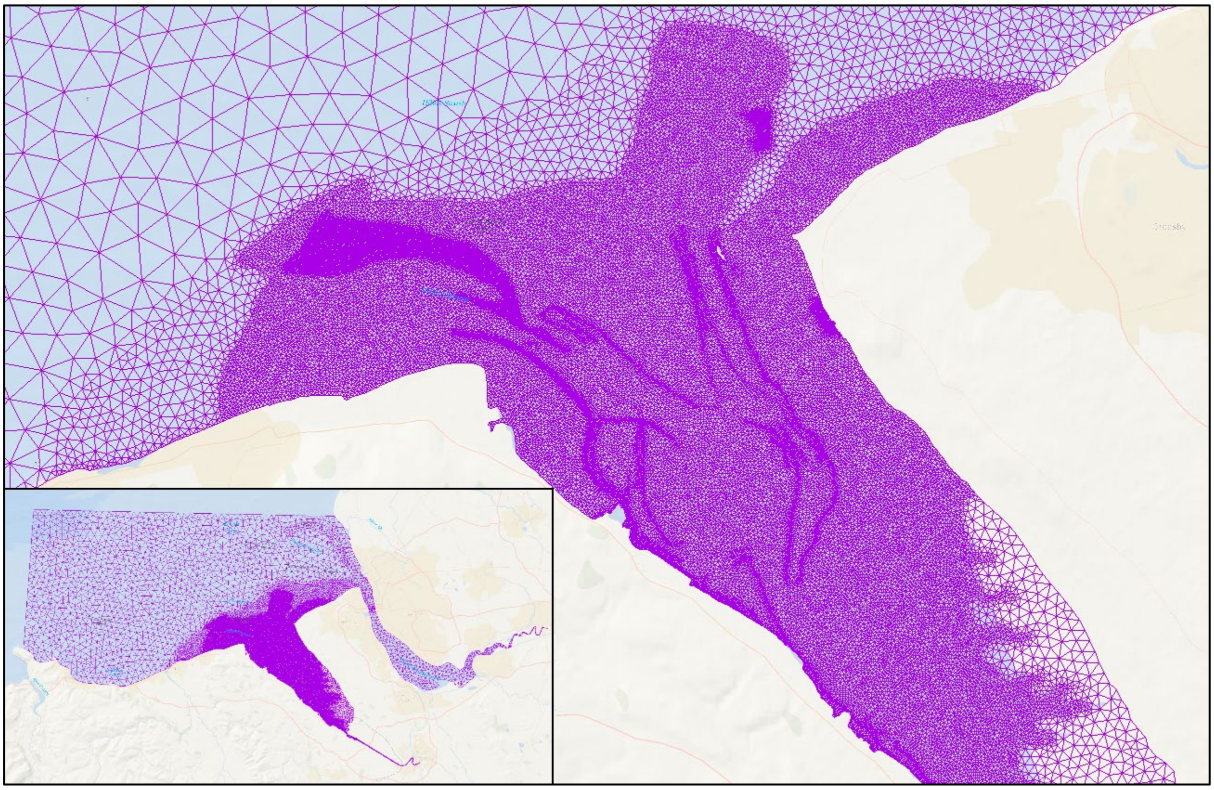


Figure 3. Model mesh with high-resolution in Dee Estuary (and wider extent as inset)

This approach enables the particular complexities of the project to be sufficiently resolved within the model, while maintaining a coarser resolution away from the site of interest to maximise computational efficiency. FM resolutions range from 1 km in offshore areas to 30 m in the main area of interest around Port of Mostyn and the location of the proposed MEPE.

The same higher resolution is also applied to the main entrance channels in order that the steeply-sided slopes are adequately represented in the model. This level of resolution is necessary to adequately represent the large vertical gradients over relatively shorter horizontal length scales (with slopes of up to around 1 in 3 in places). The resolution of the RM is 5 cells across the width of the river section (providing a transverse resolution of around 30 m).

2.2 Bathymetric and topographic data

A number of bathymetric and topographic datasets have been combined to create the model bathymetry, the extents of which (in and around Port of Mostyn) are shown in Figure 4.

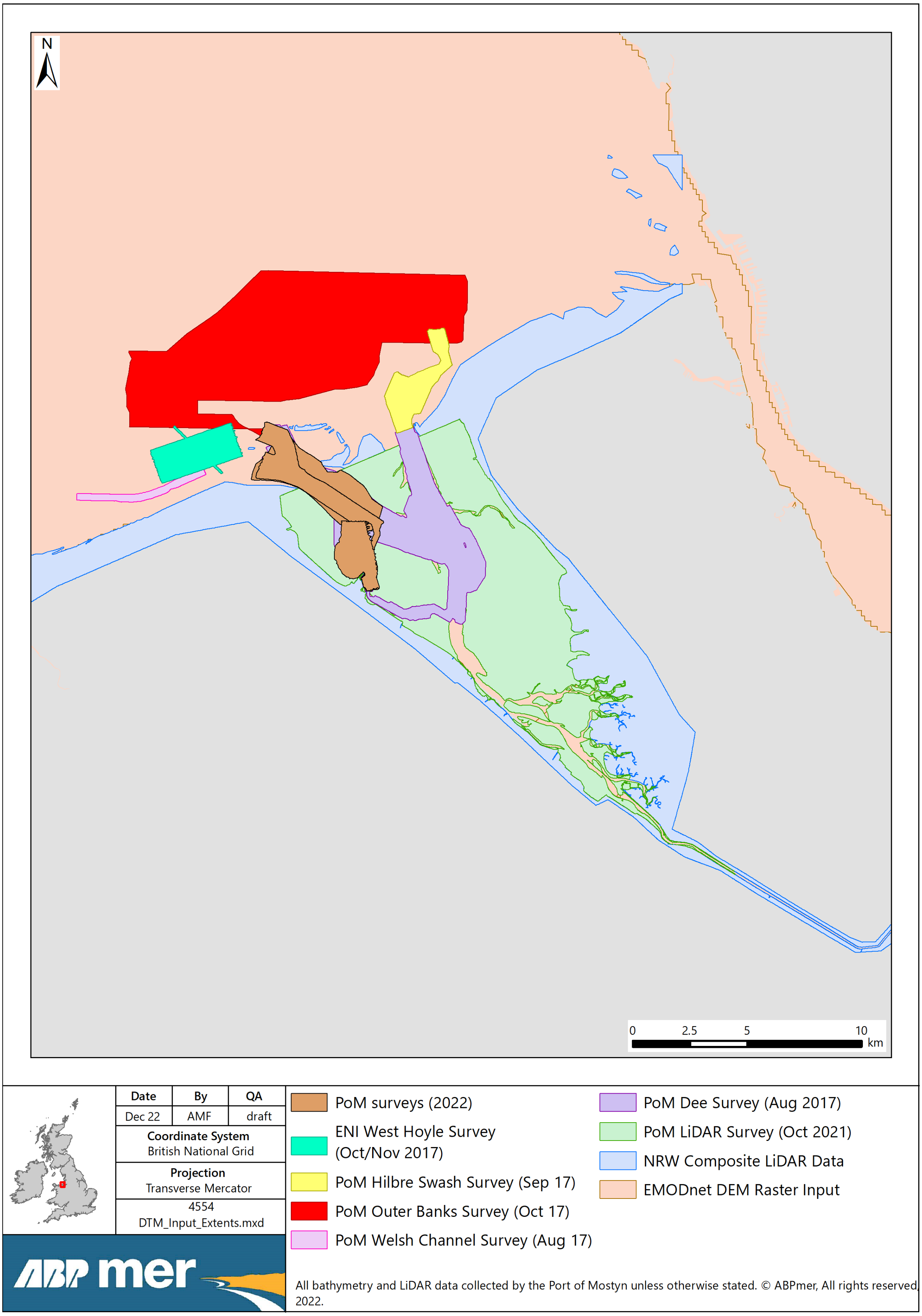


Figure 4. Extents of bathymetric survey data in and around Mostyn and Approaches

The primary data sources are listed below:

- A series of multi-beam and single-beam bathymetric surveys undertaken by the Port of Mostyn during 2022;
- A new multi-beam bathymetric survey that was commissioned by ENI UK Ltd of a section of the West Hoyle Spit (see next section) between 17 October and 29 November 2017;
- LiDAR surveys of the estuary carried out on behalf of the Port of Mostyn. Emphasis has been given to the latest (2021) survey with any gaps filled in from earlier surveys. This data provides the bathymetry for the shallower intertidal areas;
- NRW 'composite LiDAR' data for the outer coastal areas;
- A DTM from previous numerical modelling of the estuary as used for the Approach Channel monitoring (SMP, 2015); and
- Data available within the EMODnet online portal to infill any remaining gaps in coverage, and offshore subtidal areas.

Each of the datasets has been converted to the vertical datum Ordnance Datum Newlyn (ODN) to provide a spatially and temporally coherent reference system. The horizontal projection used in the model is British National Grid (BNG) and any datasets not originally in this projection were converted using ESRI ArcGIS.

The combined bathymetry was interpolated onto the model mesh using the natural neighbour method (Figure 5). In general, the bathymetry data have a higher resolution than the mesh and so interpolation will have little effect on the accuracy of the data representation within the model. In addition, Figure 6 shows the model bathymetry detail within the primary study area around the Port of Mostyn.

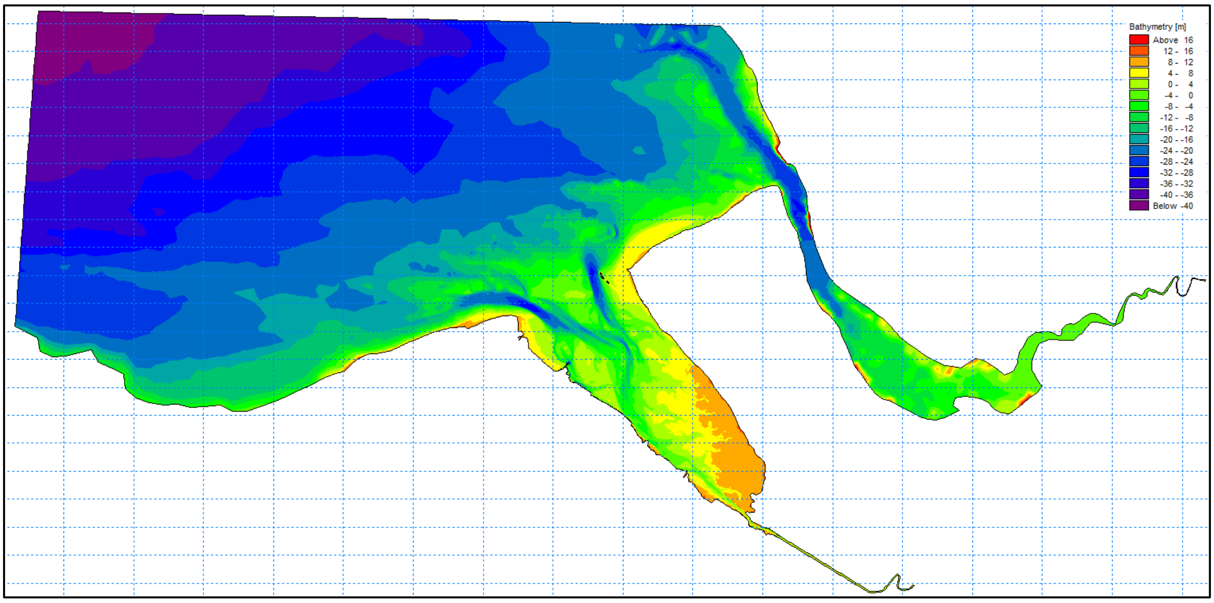


Figure 5. Interpolated model bathymetry (m relative to ODN)

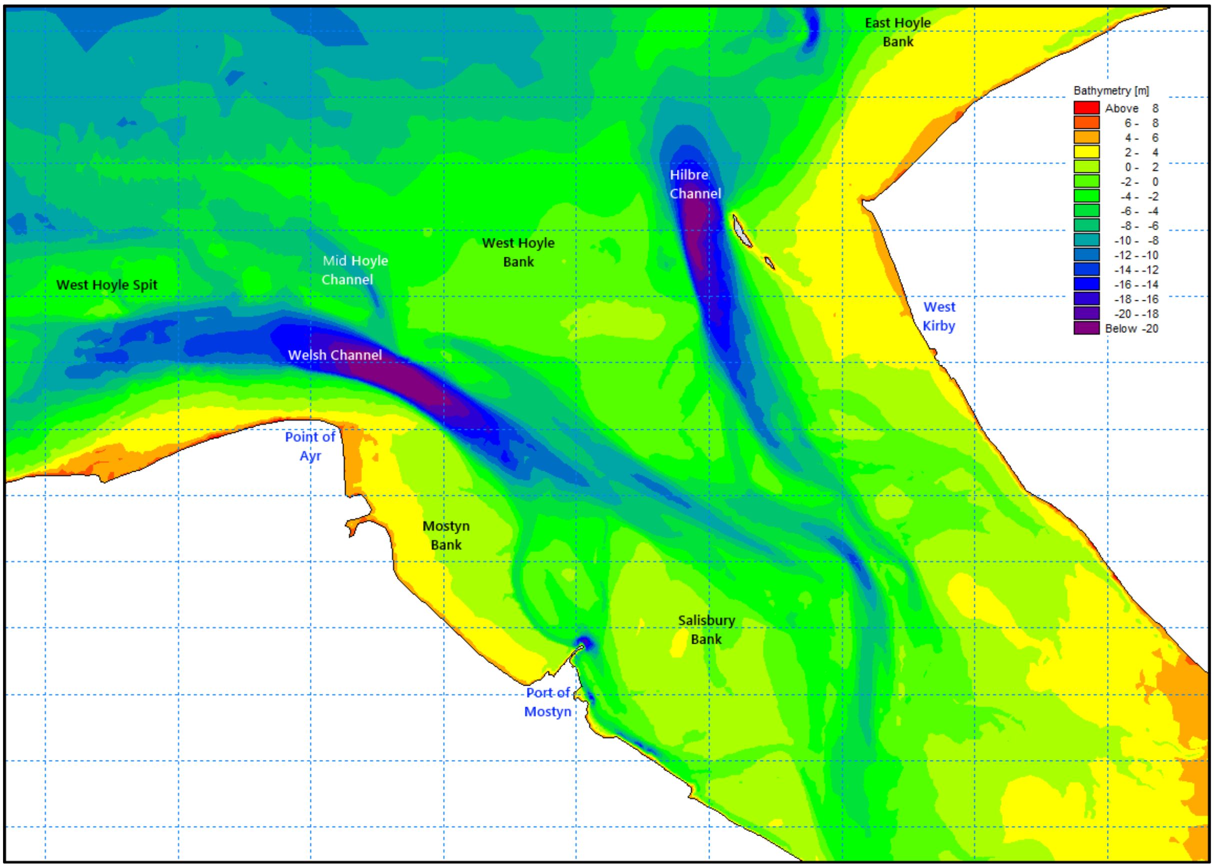


Figure 6. Bathymetry in and around Port of Mostyn and Approaches (m relative to ODN)

2.3 Hydrodynamic model

The original ABPmer hydrodynamic model was run for a period equivalent to 30 September 2017 to 1 November 2017 in order to encompass the survey deployment period (ABPmer, 2018a). The model was calibrated over the spring tide (between 17 and 24 October 2017) that coincided with the spring tide survey period and the calibration data available. Subsequently, the model was re-run (without further adjustment) for the period 10 to 17 October 2017, over predominantly neap tides, in order to validate the model performance.

Following update for use in the MEPE assessment studies, the model run period was updated and verification checks on model performance were undertaken against water level data from Mostyn (UKHO, 2022).

2.3.1 Boundaries

The model contains one open river boundary and two open offshore boundaries. The river boundary is defined by a mean discharge of 10 m^3/s (UKHO, 2022), whilst the offshore boundaries are driven by a combination of time-varying water levels and flows (Figure 7). Since the Mersey is implemented primarily to ensure volume exchange from the Irish Sea, no river discharge is included from this estuary.

Extractions from ABPmer's SEASTATES Tide and Surge model (ABPmer, 2017) were used to drive the two offshore boundaries. The ABPmer SEASTATES model has been extensively calibrated and validated against available measured datasets around the UK coastline, with NTSLF gauge sites at Llandudno and

Liverpool within the present study area (further detail on calibration of the SEASTATES Tide and Surge model is provided in ABPmer, 2017).

After comparison with tide gauge data at Llandudno and Formby, a small phase-shift of +10 minutes was applied to the offshore boundary inputs. The input at the water level driven boundary was adjusted against measured data from the tide gauge at Llandudno and Formby; the values were decreased by 0.08 m and the amplitude of the tide was increased by 9%.

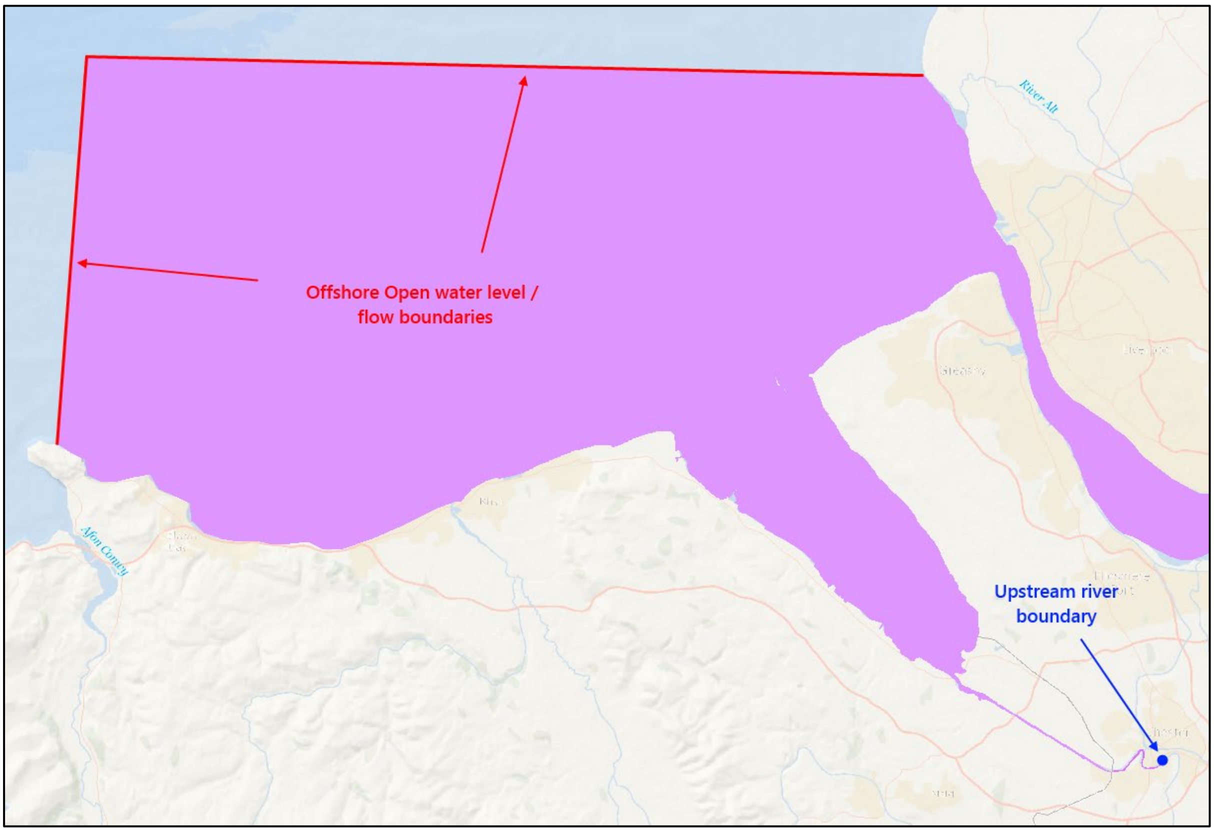


Figure 7. Model boundary locations

2.3.2 Bed resistance

Manning's roughness was selected as the bed resistance type and was defined as variable throughout the domain. Deeper areas, including deep channels, were given a higher Manning's number (representing lower bed resistance) than shallower areas, such as intertidal banks. Intermediate depth roughness values were allocated based on a scaling factor between the deep and shallow values. In addition, the main channel connecting the outer estuary to the upstream sections of the Dee was also given a lower bed roughness, to encourage tidal propagation to the tidal limit at Chester.

Having a variable bed roughness in this way encourages peak flows through the deeper channels within the estuary (where the roughness is lower); a flow characteristic observed in the survey data collected prior to model creation.

Through the model calibration stage, the response of the model, particularly the upstream sections, was found to be sensitive to the definition of the bed resistance applied. The magnitudes of the bed resistance values applied were also seen to be important in ensuring that sufficient tidal volume was able to pass through the estuary (and the Mersey) and into the upstream river sections, thus helping the model to provide representative flow conditions across the primary area of interest.

2.3.3 Additional input parameters

Further to the descriptions of the above model inputs, additional setup parameters (i.e. related to eddy viscosity and dispersion) were also applied to the baseline model. These have been defined through sensitivity testing during the model calibration stage, with parameters tuned to improve the ability of the model to describe the existing physical processes.

2.4 Sediment transport model

The study also aims to assess the potential impact on sediment transport processes, as a result of the proposed Project. This assessment is built around existing knowledge of the Dee Estuary system and informed by bespoke numerical modelling of the baseline and scheme scenarios. To achieve this, the DHI Sand Transport (ST) module has been applied, driven by the outputs from the hydrodynamic modelling described above. The following sections describe the set up of this transport module.

2.4.1 Sand transport (ST) module setup

The ST 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

Grab sampling data from the project survey and monitoring campaigns (Figure 8 and Figure 9) has been analysed for particle size distribution (Table 1 and Table 2), and the average composition of the bed material across the proposed Project area has defined the sediment grading used within the ST model.

Table 1. Particle size distribution across the site

Sample	% Composition		
	Silt (< 63 µm)	Sand (63 µm to 2 mm)	Gravel (> 2 mm)
Intertidal 1	66.7	33.3	0.0
Intertidal 2	84.9	15.1	0.0
Intertidal 3	81.5	18.5	0.0
Intertidal 4*	16.7	83.3	0.0
Intertidal 5*	1.7	98.3	0.0
Intertidal 6*	3.8	96.2	0.0
Intertidal 7*	9.3	90.7	0.0
Subtidal 1*	46.7	52.6	0.6
Subtidal 2	79.8	20.2	0.0
Subtidal 3	72.0	27.9	0.0
Subtidal 4	13.9	86.0	0.1
Subtidal 5*	9.3	90.5	0.2
Subtidal 6	4.8	95.0	0.3
Average (all samples)	**37.8**	**62.1**	**0.1**
Average* (capital dredge)	**14.6**	**85.3**	**0.1**

* Samples within the MEPE berth pocket capital dredge area

Figure 8. Project specific grab sample locations

A variety of seabed sediment types are found in the Dee Estuary (Port of Mostyn, 2013). The bed comprises recent deposits of sand and mud in a trough eroded in glacial deposits of boulder clay, silts, sands and gravel deposited by ice. The post glacial inundation of the valley by the sea started the process of sediment accretion and the underlying solid geology is now overlain generally by 20 m to over 30 m of subsequently deposited sediment.

The estuary sand is generally of uniform grading within a narrow envelope (Port of Mostyn, 2013). The majority of the sediment in the area of the Inner Channel and berthing area is a medium grained sand, with only a small proportion of finer material present. The particle size of the sand on the seabed along the whole navigation channel (outer and inner) shows little variation between offshore Prestatyn and the Port (ERM, 2007).

Table 2. Summary PSD of June 2022 monitoring seabed grab samples

Sample	% Composition Silt (< 63 µm)	Sand (63 µm to 2 mm)	Gravel (> 2 mm)
A3	36.7	63.3	0.0
A4	43.6	56.4	0.0
A5	8.5	91.5	0.0
A6	6.9	93.1	0.0
A7	0.0	100.0	0.0
A8	3.5	96.5	0.0
B2	51.0	49.0	0.0
B3	57.2	42.8	0.0
B6	0.3	99.7	0.0
C1	4.3	95.7	0.0
C2	6.1	93.9	0.0
C3	30.5	69.5	0.0
C4	34.4	65.6	0.0
D2	5.6	94.4	0.0
D3	6.2	93.8	0.0
W1	0.0	100.0	0.0
W2	0.0	100.0	0.0
W3	36.2	63.8	0.0
W4	43.2	56.8	0.0
W5	24.5	75.5	0.0
Y4	5.7	94.3	0.0
Y5	46.8	53.2	0.0
Y6	0.0	100.0	0.0

The most recent seabed grab sampling, to inform the ongoing annual monitoring for the existing dredge and disposal licences, was carried out in June 2022. The latest annual sampling campaign was unable to collect samples from three of the predefined locations as a result of natural variability in the extents and alignments of the local banks and channels (meaning the three locations in question were subtidal at the time of sampling). During the Spring 2022 survey, only relatively minor changes in habitat were recorded with key characteristics remaining broadly similar to previous monitoring at the majority of sites.

In summary, tide-swept sandflat habitat continued to extend through much of the intertidal areas surrounding the central and outer Approach Channel. This included much of the central and eastern sections of Transects A, B and Y (Sites A5-A8, B4-B6 and Y6), the western sections of Transects C and W (Sites C1-C2 and W1-W2) and Transect D (Sites D2-D3).

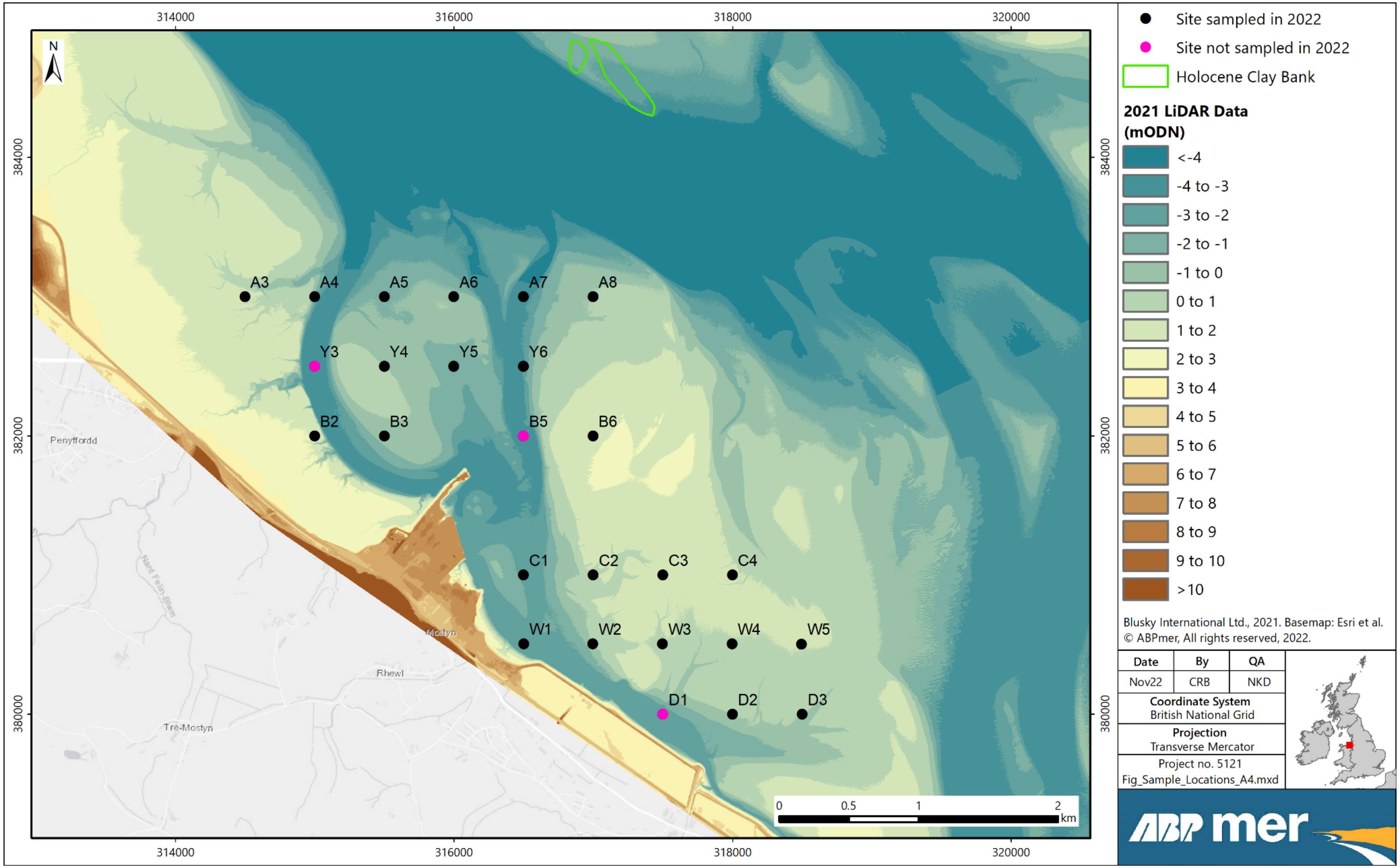


Figure 9. **Grab sampling from June 2022 across the wider study area**

2.5 Dredging operations model

The potential fate of dredge arisings and spoil from removal to licensed 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 sand transport module (see above), with the subsequent assessment using the dredge volumes from the project engineers, an understanding of the likely dredging processes and of the availability of open, suitable disposal sites.

2.5.1 Particle Tracking (PT) module setup

As with the sediment transport module (above), the PT module has also been run using the outputs of the calibrated hydrodynamic model (Section A.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.

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 assessment.

2.5.2 Model performance

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.

2.6 Spectral wave model

The wave model uses the same model grid and bathymetric data as described above for the hydrodynamic module.

2.6.1 Model parameters

Following the verification process, 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 22 frequencies, covering wave periods from approx. 0.5 to 15 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 of extreme wave events and is of limited importance at high water when waves at the site will be greatest, although the sensitivity to currents of the extreme events was examined through the verification exercise.
- Diffraction: Tested and subsequently excluded from model setup as found to be of limited importance over study area.

3 Calibration and Validation

The approach to model verification and the results of the calibration and validation exercise are provided in the following sections.

3.1 Guidelines and metrics

The model performance was assessed against a set of metrics defined in the internal model calibration guidance note maintained by ABPmer (2014). This document brings together relevant literature and guidance and offers a critique and discussion on best practice standards upon which the derived metrics are based. These metrics provide a comparative measure for the goodness-of-fit between temporal and peak features of the model predictions and measured hydrodynamic parameters.

These statistical assessments are accompanied by visual checks. Under certain conditions models can meet statistical calibration standards but appear to perform poorly in a visual comparison; conversely seemingly accurate models judged on visual comparisons can fall outside model performance defined through statistical methods.

It is also important to account for, and fully consider, any limitations or errors present in the calibration datasets before using them for model calibration purposes. Generally, systematic errors can readily be identified and corrected. However, short-term stochastic errors due, for example, to meteorological variability, are less easy to identify and account for, and thus care must be exercised when choosing the observational data to use in model calibration.

The model performance metrics used here are:

- 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;
- Mean phase difference (at high and low water). Calculated as the mean magnitude of time difference at high and low water between the model and observed data, over a spring neap cycle;
- 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;
- 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; and
- Root mean square (RMS) error. This value is calculated as the RMS value after taking account of any phase shift between datasets. Values are calculated over a defined period.

The best practice standards set out below and reported in ABPmer (2014) state recommended values that the model aims to meet:

- Water levels: Mean level differences should be within ±0.1 m to 0.2 m at the mouth of the estuary and ±0.30 m at the head, while the percentage differences should be within 10% of spring tidal ranges and 15% of neap tidal ranges. Water level phasing at the mouth should be to within ±15 minutes measured at the points of high and low water, ±25 minutes at the head. RMSE (Root-Mean-Square Error) values should be less than 0.20 to 0.25; and

- Flows: Modelled speeds should be within ±10% to 20% of peak observed speeds, while modelled directions should be within ±15° of observed directions in an estuary; RMSE values should be less than 0.20 to 0.25.

The reason for accommodating some level of discrepancy between the observations and model is to account for any differences between the data acquisition (discrete point in space and time) and the model result (depth- and time-averaged grid cell values). It is, therefore, not considered necessary to further justify discrepancies between modelled and measured values that lie within these standards. Larger discrepancies can be tolerated where the accuracy of observational data is questionable, or known meteorological conditions occurred which are not simulated in the model. Where such discrepancies arise, further discussion should be provided.

In addition, the model should simulate 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. Directionally, any distinct rectilinear or rotary change with time should be simulated, thus showing the processes and interaction with the seabed are being correctly reproduced.

Timeseries plots of the key hydrodynamic parameters (water level, flow speed and direction) are used to assess the visual 'fit' of the model output against the calibration and validation datasets.

3.2 Calibration data

A range of data was collected over varying temporal and spatial scales to aid the original calibration and validation of the estuary model. These include measurements from tide gauges and from surveys conducted by ABPmer (ABPmer, 2018a). The collection sites for each dataset are shown in Figure 10.

3.2.1 Static acoustic wave and current meter (AWAC) and Aquadopp data

As part of ABPmer's survey programme developed for the Port of Mostyn (ABPmer, 2018a), five survey deployment locations in the outer estuary were identified and were sampled using a combination of AWAC and Aquadopp instruments. These were deployed for a one-month duration, starting on 8 October 2017. These instruments recorded the following data at 10-minute intervals, relevant to the hydrodynamic calibration:

- Water level in relation to the device;
- Current speed and direction through depth, and across transects; and
- Wave conditions (height, period and direction.

Due to water levels being measured relative to the depth of the instruments instead of true values, the water level data collected by the AWACs were subsequently calibrated against tide gauge data.

3.2.2 Tide gauges

Alongside water level data from each of the five survey deployment locations data from the tide gauge at Flint, and tidal predictions at Connah's Quay and Chester (Figure 10) were also obtained, in order to assess the model performance within upstream sections of the Dee Estuary.

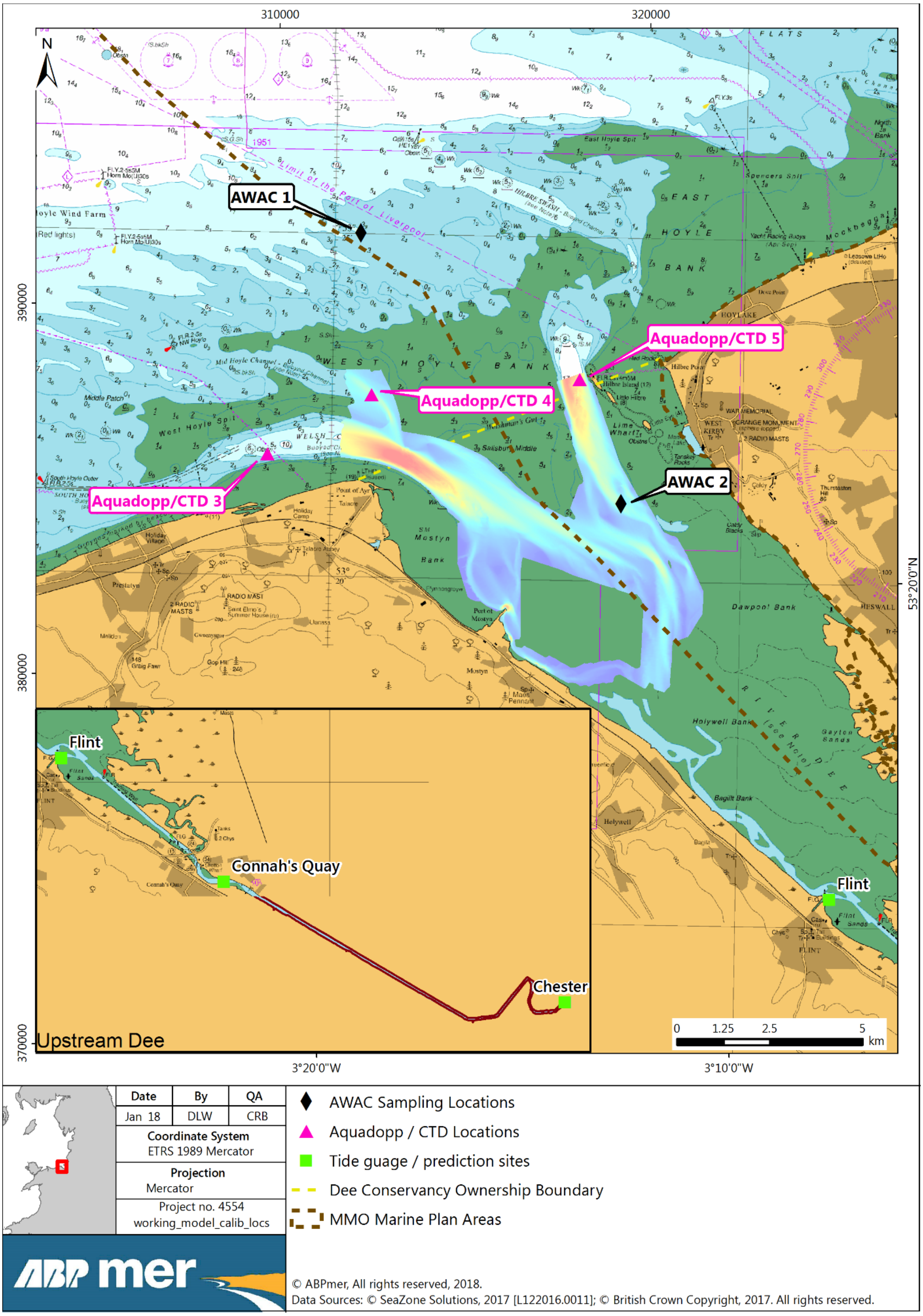


Figure 10. AWAC and ADCP calibration data locations and tide gauge / prediction sites

3.2.3 Mobile acoustic doppler current profiler (ADCP) data

ABPmer's survey programme (ABPmer, 2018a) also included two mobile (boast based) ADCP transect campaigns; one in the Welsh Channel and one in the Hilbre Channel. The data was collected from cross-sectional profiles of flows through the water column at various sites along the estuary and the results were then compared to depth-averaged cross-sectional profiles generated from the model outputs.

These comparisons indicate whether peak flows (and the distribution of flows across the channels) from the model are in the correct locations at the correct point in the tidal cycle and are following the channels accurately.

3.2.4 Additional data

As a further verification process it was considered valuable to check the modelling results against data collected during a previous survey (i.e. in addition to the recent ABPmer surveys). A number of different hydrodynamic surveys have been carried out in the outer Dee Estuary including several that have informed previous proposed developments at the Port of Mostyn. Of these past studies, the survey work by HR Wallingford Ltd. (HRW, 2012) was used for a semi-quantitative comparative analysis.

For these HRW surveys, shallow water ADCP data was collected from three cross-shore transects across Mostyn Bank, in order to inform the original Mostyn Energy Park proposal (Port of Mostyn, 2013). Data from this survey was selected firstly because it describes the hydrodynamic conditions across the Mostyn Bank, which lies adjacent to the Port of Mostyn. This survey was also selected because the surveys are relatively recent and cover an area that is unlikely to have changed greatly following recent localised shifts in the channel alignments in this part of the estuary.

3.3 Hydrodynamic model calibration results

3.3.1 Water levels

The modelled water levels have been extracted and plotted against the measured data at each of the five survey deployment sites (see Figure 10 for locations), along with the tide gauge site at Flint and the tidal predictions at Connah's Quay and Chester. These timeseries comparisons are provided in Figure 11 and Figure 12.

In each case, the model water levels are plotted in red, the AWAC/Aquadopp survey data is plotted in black, and the available tide gauge measurements/tidal predictions are plotted in blue.

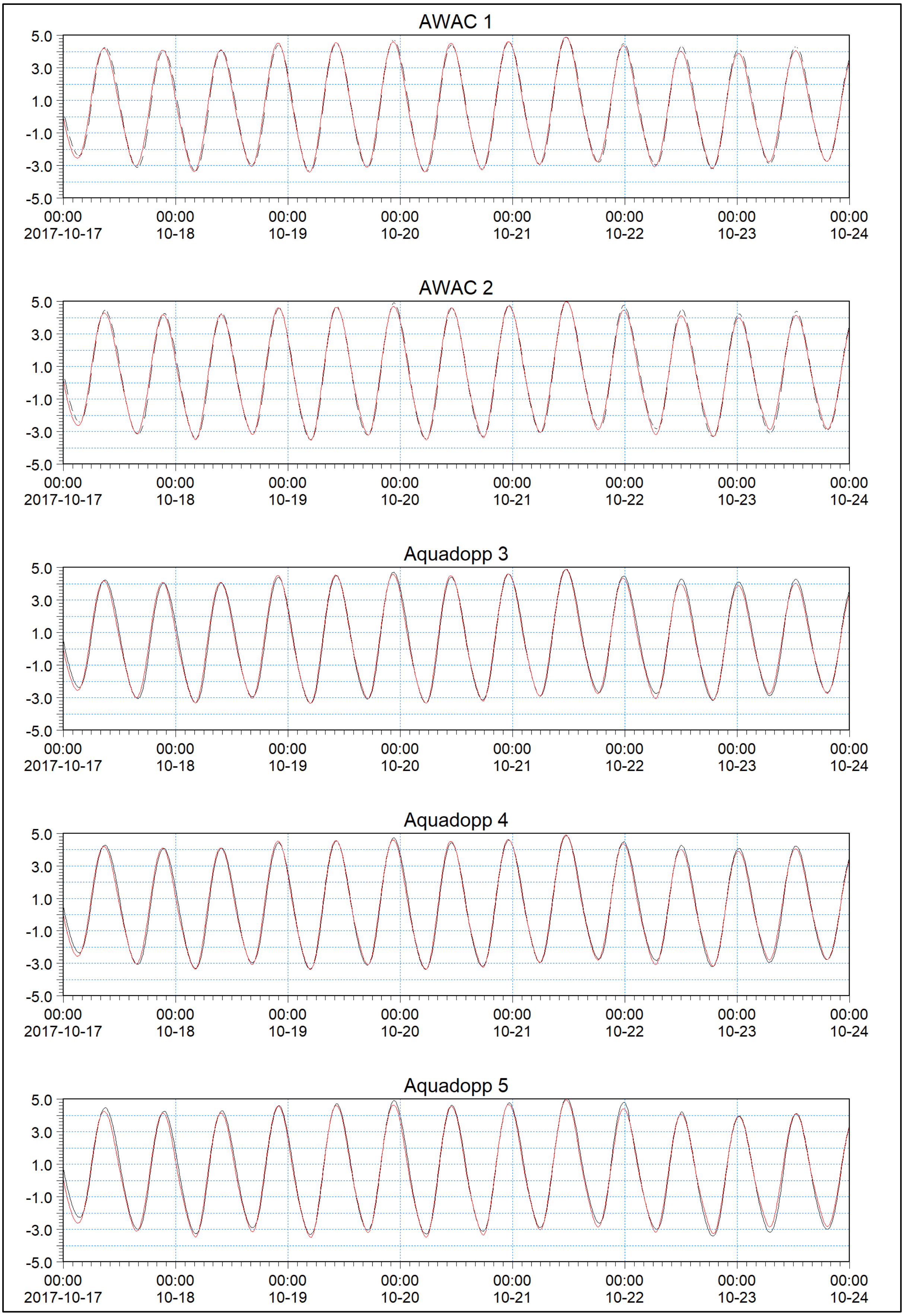


Figure 11. Timeseries comparison of surveyed water levels for calibration period (model output in red)

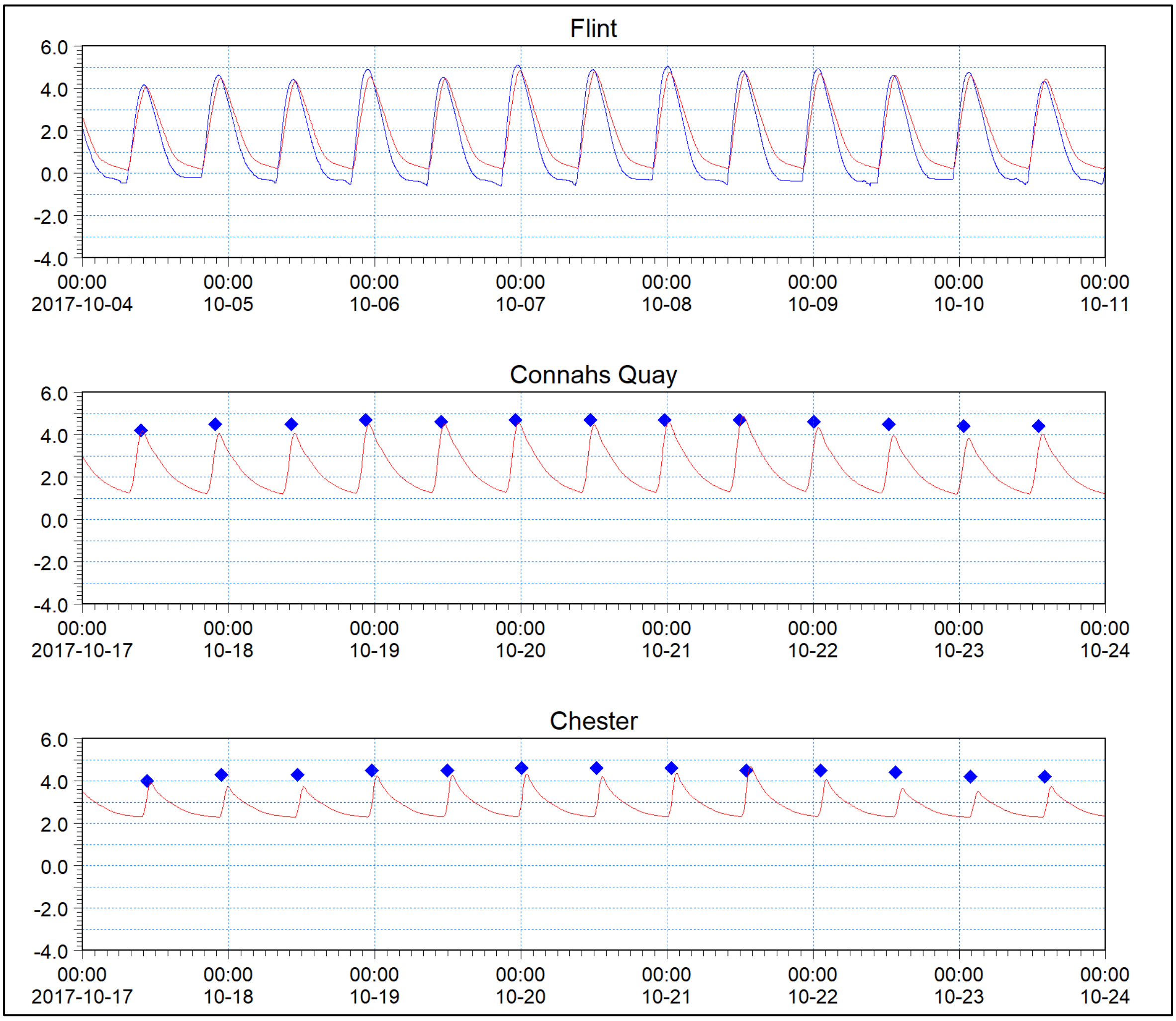


Figure 12. Timeseries comparison of upstream water levels for calibration period (model output in red, predicted HW elevations only for Connah's Quay and Chester)

In addition to the timeseries comparison, a series of statistics have been calculated to describe the model fit to the data. The results of this assessment (against the metrics defined in Section 3.1) are provided in Table 3.

It can be seen from the timeseries comparison, and the associated statistical analysis, that the model is performing well in representing water levels throughout the study area. The bias between the model and the measured survey data is less than 0.2 m for both HW and LW levels at all locations, with many of sites showing a bias of ±0.05 m. The phasing of the tide in the model is also well within 10 minutes in the relative timings of measured HW and LW; whilst the RMS error is less than 0.2 at all sites.

When compared against the tide gauge data at Flint, and the tidal predictions upstream at Connah's Quay and Chester, the model continues to perform relatively well, particularly when compared to HW elevations. The tidal predictions at Connah's Quay and Chester do not provide for LW elevations, hence no calibration statistics are available for these parameters at these locations, and the timeseries plots provide a comparison against predicted HW elevations only.

It is further noted that the model boundaries include the effects of meteorological surge in order to improve the calibration against the measured data in the primary area of interest. Tidal predictions for Connah's Quay and Chester only provide the astronomic tidal component and, consequently, are not directly comparable to the model output. They do, however, give a useful insight into the tidal propagation, into upstream sections of the model, allowing general HW elevations and phasing to be compared. The surge component would have increased actual water levels therefore a negative bias should have resulted. Table 3 shows that this was the case.

Table 3. Water level calibration statistics

Metric	Location							
	AWAC 1	AWAC 2	Aquadopp 3	Aquadopp 4	Aquadopp 5	Flint	Connah's Quay	Chester
Mean HW WL diff (m)	-0.06	-0.15	-0.06	-0.05	-0.14	-0.21	-0.23	-0.37
Mean LW WL diff (m)	0.01	-0.05	-0.04	-0.03	-0.11	0.71	NA	NA
Mean HW phase diff (min)	2	2	2	2	1	23	18	28
Mean LW phase diff (min)	2	8	5	6	7	41	NA	NA
Mean HW diff (% tidal range)	-0.8	-2.0	-0.9	-0.6	-1.9	-3.9	NA	NA
Mean LW diff (% tidal range)	0.1	-0.7	-0.5	-0.4	-1.5	13.6	NA	NA
RMS Error	0.16	0.18	0.16	0.15	0.20	0.61	NA	NA

Note: Some tide gauge / prediction sites dry out under LW conditions;
Green Indicates value is within calibration guidance recommended values;
Orange Indicates value is outside.

The majority of performance metrics are well within the recommended values (identified by the green values in Table 3, indicating the model is performing to an acceptable level of accuracy. Where values fall outside the recommended values, these relate to the comparison of:

- Modelled LW levels against the Flint tide gauge; and
- HW only predictions at Connah's Quay and Chester.

At these locations, the part of the variance shown in the model calibration is likely to be a result of the sites drying out at low water, whilst the model bathymetry is sufficiently deep to allow further ebb drainage. It is further noted that the bathymetric data and model grid resolution in the River Dee (up-estuary of Connah's Quay) are both considerably coarser than across the primary area of interest in and around the Port of Mostyn and Approaches. Here the calibration suggests that the drainage from the low water channel is slightly impaired in the model, or the average freshwater flow used for the model was larger than occurred on the day of the measurements. This does not significantly affect the majority of the tidal propagation.

Overall, it is considered that water levels are well-represented by the numerical model.

3.3.2 Currents

As with water levels, the model outputs of current speed and direction have been extracted and plotted against the equivalent data from each of the five survey deployment sites (see Figure 10 for locations). The results of the timeseries comparison are shown in the following sections.

Timeseries

At each location, timeseries plots of depth-averaged current speed and direction are shown in Figure 13 and Figure 14. Model outputs are plotted in red with AWAC/Aquadopp data plotted in black.

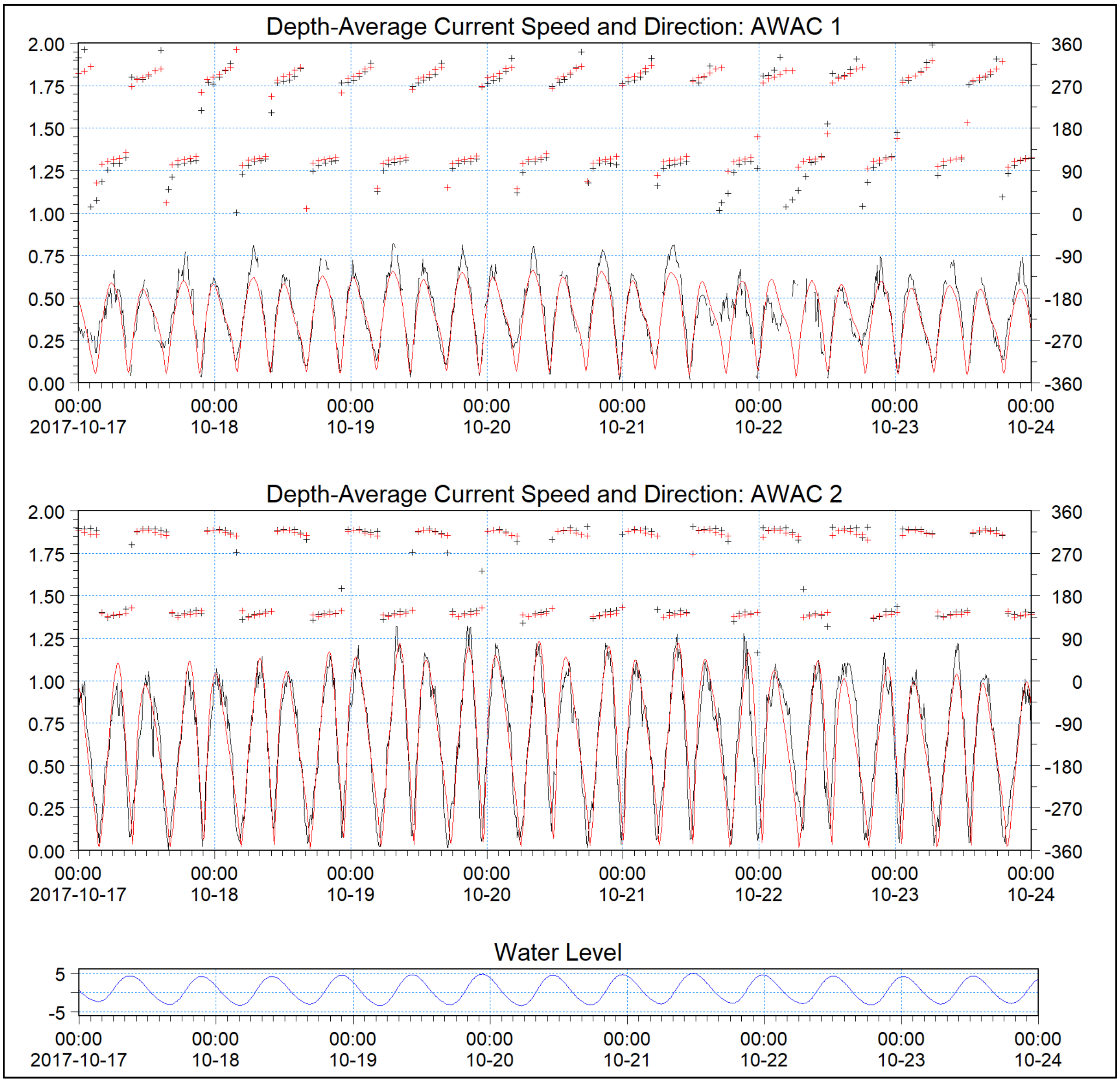


Figure 13. Timeseries comparison of AWAC current speed and direction for calibration period (model output in red)

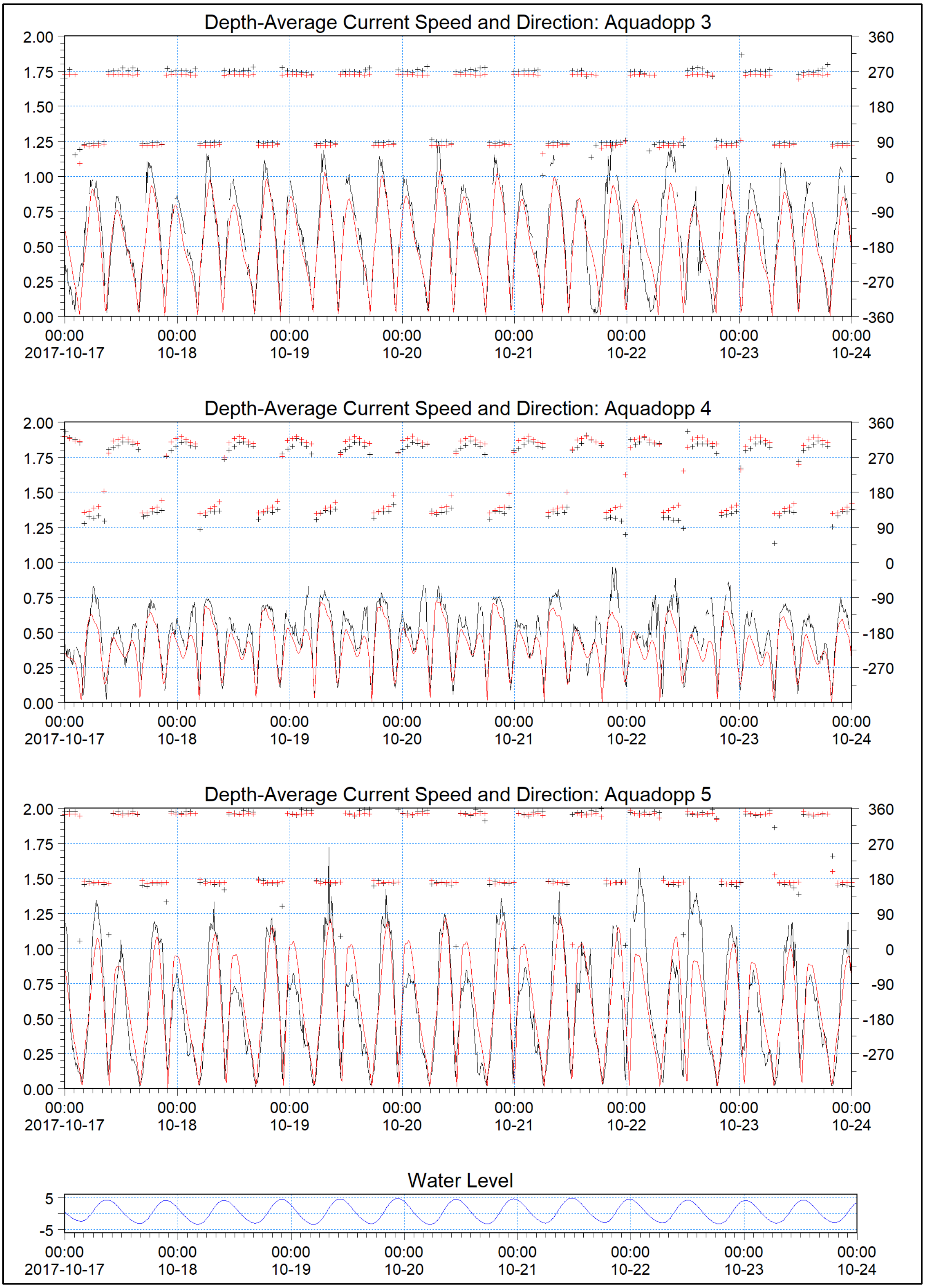


Figure 14. Timeseries comparison of Aquadopp current speed and direction for calibration period (model output in red)

In addition to the timeseries comparison, a series of statistics have been calculated to describe the model fit to the data. The results of this assessment (against the metrics defined in Section 3.1) are provided in Table 4.

Table 4. Current speed and direction calibration statistics

Metric	Location				
	AWAC 1	AWAC 2	Aquadopp 3	Aquadopp 4	Aquadopp 5
Mean Ebb speed diff (% peak)	-5.4	-3.1	-11.1	-14.7	0.6
Mean Flood speed diff (% peak)	-16.3	-3.8	-14.9	-12.3	-8.1
Mean Ebb direction diff (°)	5.9	-1.6	-8.3	20.9	-2.1
Mean Flood direction diff (°)	7.0	-3.9	-7.4	6.9	1.0
RMS Error	0.14	0.11	0.20	0.13	0.20

Green Indicates value is within calibration guidance recommended values;
Orange Indicates value is outside.

It can be seen from the timeseries comparison, and the associated statistical analysis, that the model is performing well in representing currents (both speeds and directions) throughout the study area. The bias between the model and the measured survey data is well within 20% of peak values on both the flood and ebb stages, with many locations showing levels well within 10% of peaks. The majority of sites reveal that peak flow directions are well within the ±15° guidance limit; whilst the RMS error is less than 0.2 at all sites.

The one occurrence of the calibration guidance statistics not being met is shown when comparing the ebb flow direction at Aquadopp 4 (located within Mid Hoyle Channel – see Figure 10). At this site, the modelled ebb directions are shown to be aligned slightly more clockwise (towards the north), than the measured data (as evident in Figure 14). Given the variable nature of the channel alignments at the entrance to the Dee Estuary, it is possible that the channel alignment has shifted between the survey (carried out in August 2017, and which provided the bathymetry data for this section of the model), and the survey deployment during October 2017.

This potential is supported, somewhat, by a similar shift (although of a lesser magnitude) when comparing the modelled and measured flood tide at this location. Irrespective of the slight direction bias at the Aquadopp 4 location, the model is shown to perform well in switching the tide (both in timing and rate of switch) between flood and ebb tidal states (Figure 14).

Whilst the model data shows a good representation of the field measurements it should be noted that:

- The model generally under-represents the magnitude of flows at the different locations. During the period of calibration there was generally a small positive surge occurring in Liverpool Bay, which is incorporated into the model boundary setup; and
- Significant wave events (not included in the modelling) also occurred, particularly between 21 October and 23 October 2017. A detailed analysis of the timeseries shows that during this period, the general flow speed distribution was changed, relative to the rest of the timeseries, particularly in the outer measurement locations. At AWAC 1 flow speeds were reduced, particularly on the flood tide by *circa* 0.2 m/s. Within the entrance channels, there were generally increased flows, but these were predominantly on the flood in the Welsh and Mid-Hoyle Channels to the west (AquaDopp's 3 and 4) but on the ebb in the Hilbre Channel (Aquadopp 5), see Figure 13 and Figure 14. This effect was up to 0.5 m/s (*circa* 50%) in the Hilbre Channel and potentially indicates wind/wave events could significantly change sediment

transport processes. However the data from AWAC 2, located just up-estuary of the outer banks, shows that the meteorological/wave effects do not penetrate to this location.

In general, the model replicates the following features of the flow regime throughout the Dee Estuary:

- Flood flow speed dominance in the Welsh, Mid-Hoyle and Hilbre Channels (albeit less defined in the latter);
- The double peak in ebb flows in the Mid-Hoyle Channel, which corresponds with a change from clockwise to anti-clockwise rotation;
- The general rotational tidal flows in the Mid-Hoyle Channel, compared to constant directions within the Welsh and Hilbre Channels; and
- The rotational flow pattern, particularly on the ebb tide, at the outer location (AWAC 1).

Cross-channel profiles

In addition to the comparison of timeseries at survey deployment locations, the model performance has also been qualitatively compared against the general cross-channel flow profiles available from the ADCP survey transects (ABPmer, 2018a). The ADCP transect profiles provide cross-channel, and vertical flow structure within the Welsh and Hilbre Channels. Although the model is presently run in 2D (depth averaged) mode (hence, it does not differentiate flows through the water column), the 2D element to the flow regime within these channels can be compared against the survey data.

Peak flood and peak ebb tidal flow velocity maps have been extracted from the numerical model output, focussing on the Welsh (Figure 16; Figure 18) and Hilbre (Figure 20; Figure 22) Channels. These plots reveal cross-channel variation in flow (i.e. highlighting that peak speeds on the flood tide are more aligned to one side of a channel than another; current directions vary from one side of the channel to the other, etc.).

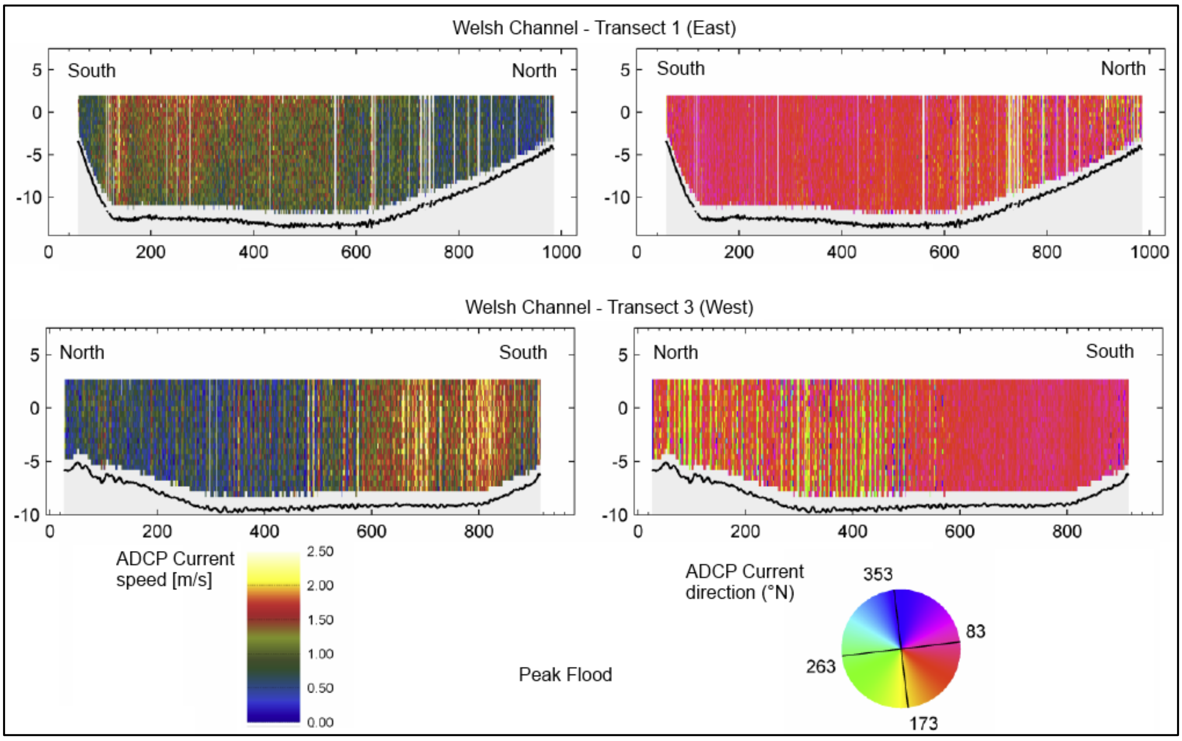
The equivalent peak flood and ebb transect profiles from the ADCP survey have also been extracted from the survey report (ABPmer, 2018a) and the flow characteristics compared. The plots, and a discussion of the model performance against the measured data, are provided below.

Figure 15 shows the ADCP transect profile data from the survey campaign, within Welsh Channel, at the appropriate time of peak flood flows.

The ADCP survey data shows a distinct split in the flow alignment on the flood tide, with peak flows generally observed on the south side of the channel (peak speeds of up to around 2 m/s), and generally uniformly distributed throughout the water column. Flow speeds over the northern part of the channel are notably slower, at around 0.5 to 0.7 m/s). The same pattern is seen on both transects, with higher flows observed on Transect 3.

With regard to flow direction, currents pass through Transect 1 in a generally uniform direction, with peak flow directions of around 100°N. Along Transect 3, peak flow speeds along the southern edge of the channel also show directions of 100°N (uniform with depth), but the northern end of the transect shows a slightly more southerly flow (albeit at much lower speeds).

Figure 16 shows the extracted model flow speeds within the Welsh Channel over a peak flood tide (with the locations of the two ADCP transect profiles highlighted).



Note the switch in transect profile orientation between Transect 1 and Transect 3

Figure 15. **ADCP transect profiles of current speed (left pane) and direction (right pane) in Welsh Channel – Peak Flood**

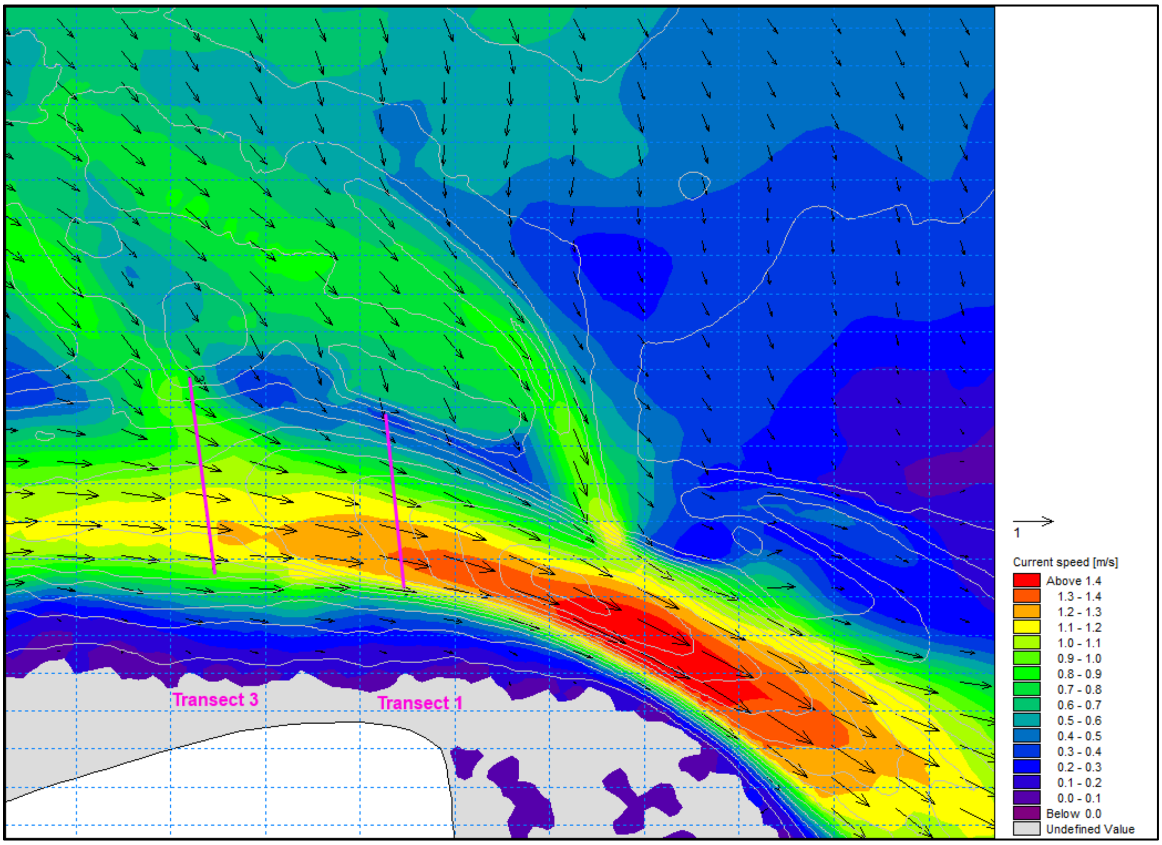
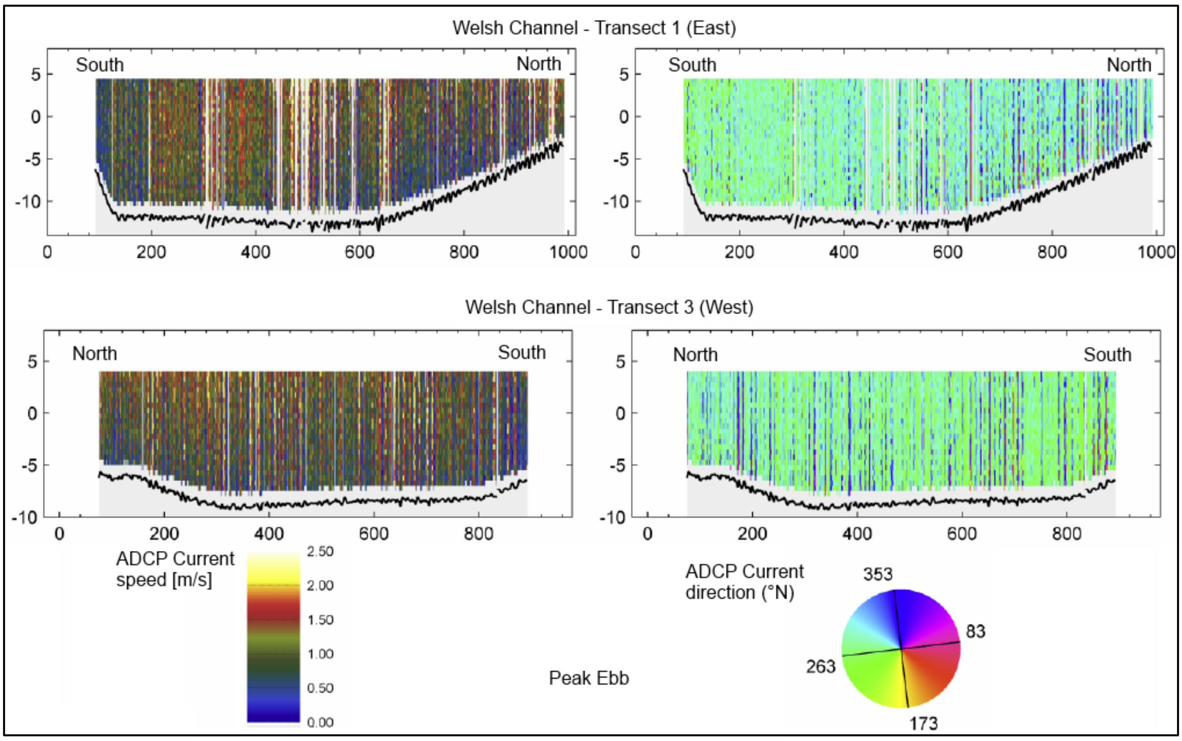


Figure 16. **Map plot of modelled (depth averaged) current speed in Welsh Channel – Peak Flood**

A very similar flow pattern is shown in the depth-averaged model output, with the peak flow speeds being seen along the southern edge (1.2 to 1.3 m/s) of the channel, and notably lower flows at the northern ends of the two transects (0.4 to 0.6 m/s). Modelled flow through Transect 1, and along the southern part of Transect 3, is generally uniform at around 100°N (aligned to the orientation of the channel). To the north of Transect 3, flow can be seen joining the main Welsh Channel via a secondary channel through West Hoyle Spit (as can be seen in the model bathymetry in Figure 6, and bathymetric contours on Figure 16). This joining flow is oriented more southerly (aligned to the secondary channel), at around 140°N.

Comparison of Figure 15 and Figure 16 show that the model is replicating the flow patterns spatially within the channel as well as at a single point. Figure 17 shows the ADCP transect profile data from the survey campaign, within Welsh Channel, over peak ebb tide.



Note the switch in transect profile orientation between Transect 1 and Transect 3

Figure 17. ADCP transect profiles of current speed (left pane) and direction (right pane) in Welsh Channel – Peak Ebb

On the peak ebb tide, the ADCP survey data shows a more uniform flow alignment through the Welsh Channel than during the flood, with peak flows generally observed over the central part of the channel. Current speeds are lower than on the flood (peak speeds generally of around 1.5 m/s), and again generally uniformly distributed throughout the water column. The same pattern is seen on both transects. With regards flow direction, currents pass through Transects 1 and 3 in a generally uniform direction, with peak flow directions of around 280°N. This general pattern is again well represented in the model (Figure 18).

In the Hilbre Channel, the two ADCP transects represent the flows in the wider channel entrance and at the narrow constriction

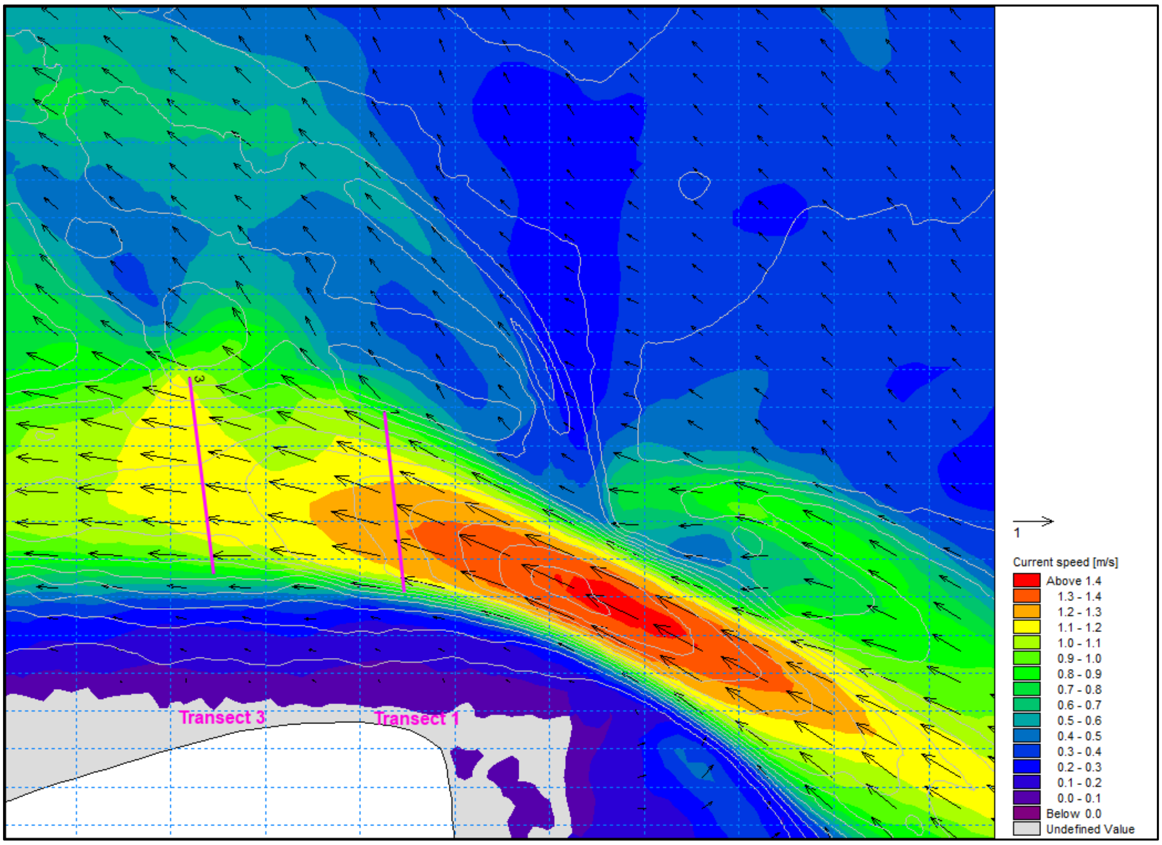
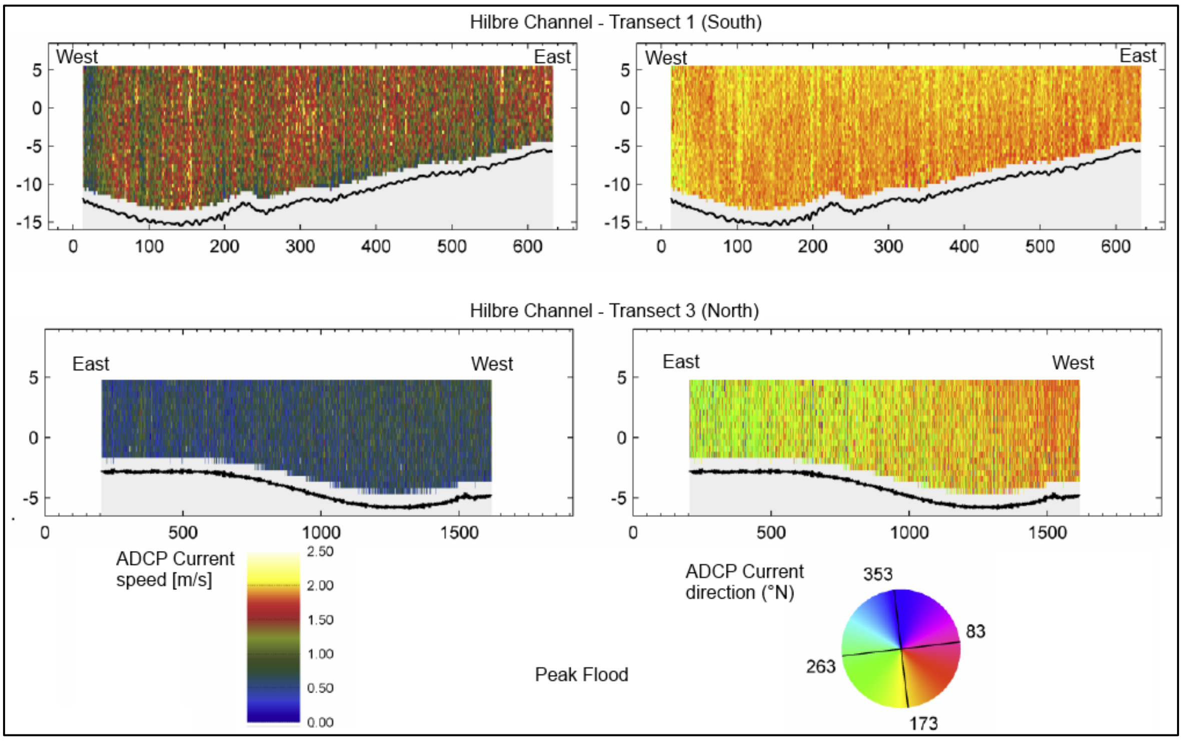


Figure 18. Map plot of modelled (depth averaged) current speed in Welsh Channel – Peak Ebb



Note the switch in transect profile orientation between Transect 1 and Transect 3

Figure 19. ADCP transect profiles of current speed (left pane) and direction (right pane) in Hilbre Channel – Peak Flood

On the eastern side of the estuary, on the flood tide, the ADCP survey data shows a distinct variation in the flow characteristics between Transect 3 (to the north of the channel entrance) and Transect 1 (in the narrow section to the south of Hilbre Island). As a result of the channel constriction, peak flood flow speeds through Transect 1 are notably faster (around 1.7 m/s) than through Transect 3 (around 0.7 m/s). Flow directions at Transect 1 are in a generally uniform direction of around 160-170°N. This is similar along the western side of Transect 3, but swing round to 200-210°N on the eastern side approximately aligned with the bed contours, as flows approach from both side of the channel.

As shown in Figure 20 this general pattern at the two transects is replicated in the model, with similar magnitudes at Transect 3. At Transect 1, however, at the time of the field measurements flows were faster than the model.

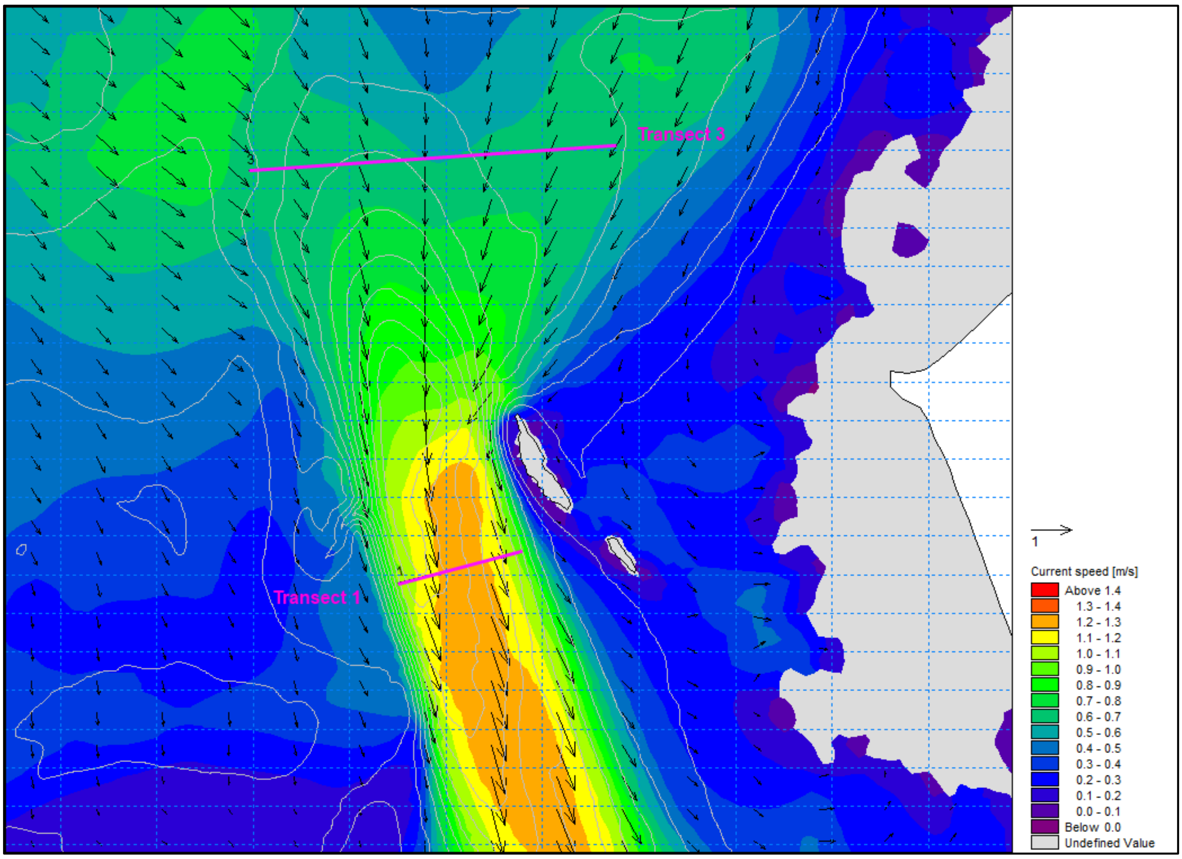
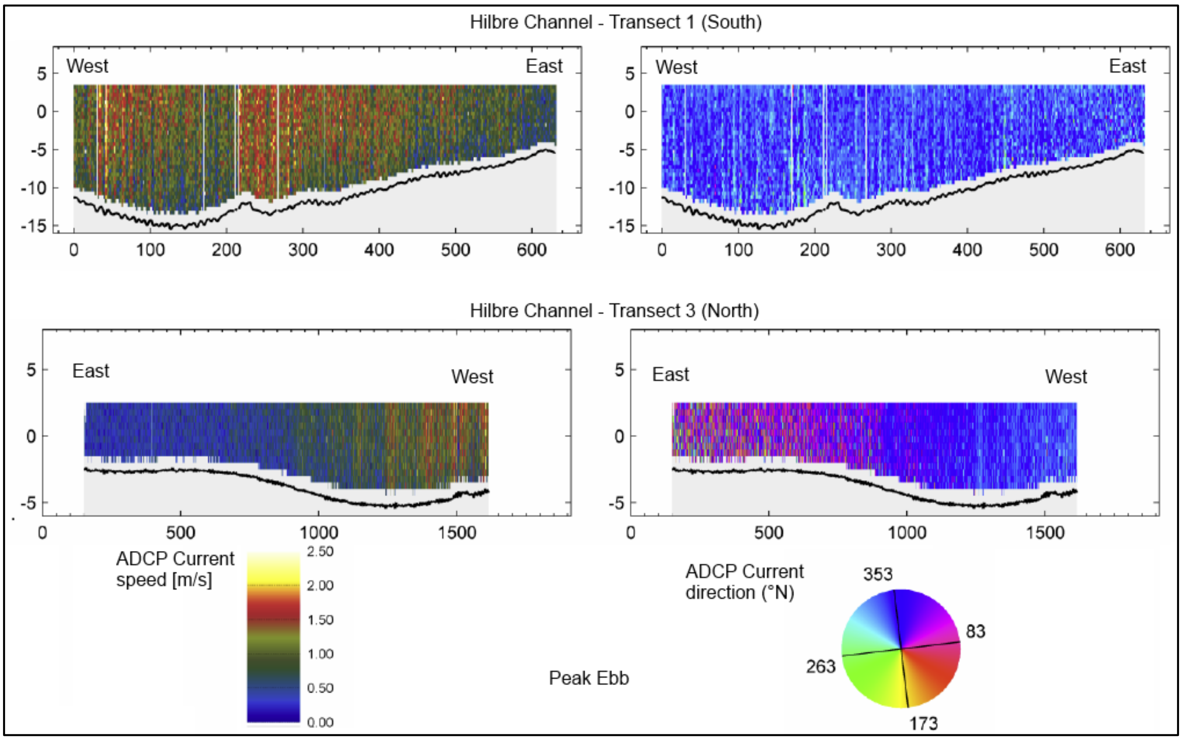


Figure 20. Map plot of modelled (depth averaged) current speed in Hilbre Channel – Peak Flood

On the peak ebb tide, the ADCP survey data (Figure 21) shows a more notable split in the flow characteristics through the Hilbre Channel, with peak flows (up to *circa* 1.5 m/s nearer the surface) generally observed more towards the western side of the channel and reducing up to about 0.5 m/s over the shallower eastern half, particularly at Transect 3.

At Transect 1 there is a secondary peak in flow in the centre of the channel which extends to the bed; whereas either side, flows are distinctly lower near the bed. Current speeds are slightly lower on the flood. In the model (Figure 22), the peak flows at Transect 1 are just to the west of the channel centreline, as seen in the ADCP Transect. However, the second area of high flows towards the west end of the Transect is not evident in the depth-averaged flows.



Note the switch in transect profile orientation between Transect 1 and Transect 3

Figure 21. ADCP transect profiles of current speed (left pane) and direction (right pane) in Hilbre Channel – Peak Ebb

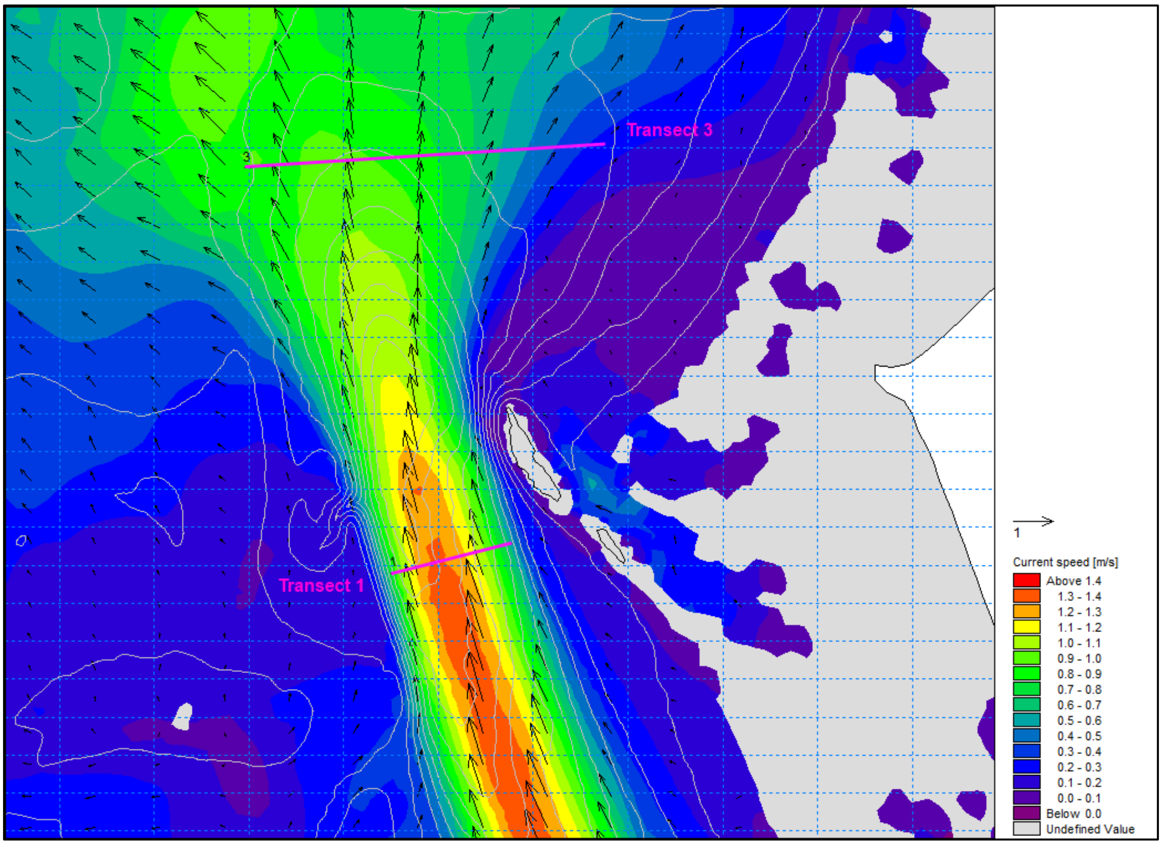


Figure 22. Map plot of modelled (depth averaged) current speed in Hilbre Channel – Peak Ebb

At Transect 3 the model shows very good agreement with flow speed, direction and the location of change across the section. With regards flow direction, currents pass through Transect 1 in a generally uniform direction, with peak flow directions of around 350°N. Through Transect 3, a similar shift in flow direction is seen as on the flood tide. The flows exiting the western side of the transect flow around 350°N, rotating around to 30°N towards the eastern side, again conforming to the bathymetry.

Overall, when considering the results of the model calibration exercise, it is considered that depth-averaged flow characteristics are well-represented by the numerical model in both channels and reflect the flow patterns imposed by the bathymetry.

3.4 Hydrodynamic model validation results

A neap tide has been chosen for the original model validation period, during the period 10 to 17 October 2017.

3.4.1 Water levels

The same locations (Figure 10) have been compared for the purpose of validation over the neap tides and are presented in the same format in Figure 23 and Figure 24, with the statistical performance metrics calculated in Table 5.

Table 5. Water level validation statistics

Metric	Location							
	AWAC 1	AWAC 2	Aquadopp 3	Aquadopp 4	Aquadopp 5	Flint	Connah's Quay	Chester
Mean HW WL diff (m)	0.20	0.10	0.27	0.17	0.04	0.07	-0.09	-0.09
Mean LW WL diff (m)	-0.14	-0.25	-0.11	-0.23	-0.36	NA	NA	NA
Mean HW phase diff (min)	-7	-7	-8	-8	-9	18	28	47
Mean LW phase diff (min)	-9	-7	-6	-6	-6	NA	NA	NA
Mean HW diff (% tidal range)	3.8	1.7	4.8	3.0	0.7	-0.1	NA	NA
Mean LW diff (% tidal range)	-2.5	-4.2	-2.0	-4.1	-6.2	NA	NA	NA
RMS Error	0.16	0.15	0.21	0.16	0.20	NA	NA	NA

Green Indicates value is within calibration guidance recommended values;
Orange Indicates value is outside.

It can be seen from the timeseries comparison, and the associated statistical analysis, that the model continues to perform well in representing water levels throughout the study area. The bias between the model and the measured survey data is well within the ±15% of neap tidal ranges, for both HW and LW levels, at all locations, with the majority of sites showing a bias within ±5%. Actual levels, however, are higher at HW and lower at LW for all measured sites, some of which exceed the required metrics. This indicates that the model is creating a larger tidal range than occurred. The semi-diurnal inequality between the 1st and 2nd tides on any day is replicated. The phasing of the tide in the model is also well within the 10-minute acceptance metric measured at HW and LW at the deployment sites, and within ±25 minutes at the upstream tide gauge at Flint.

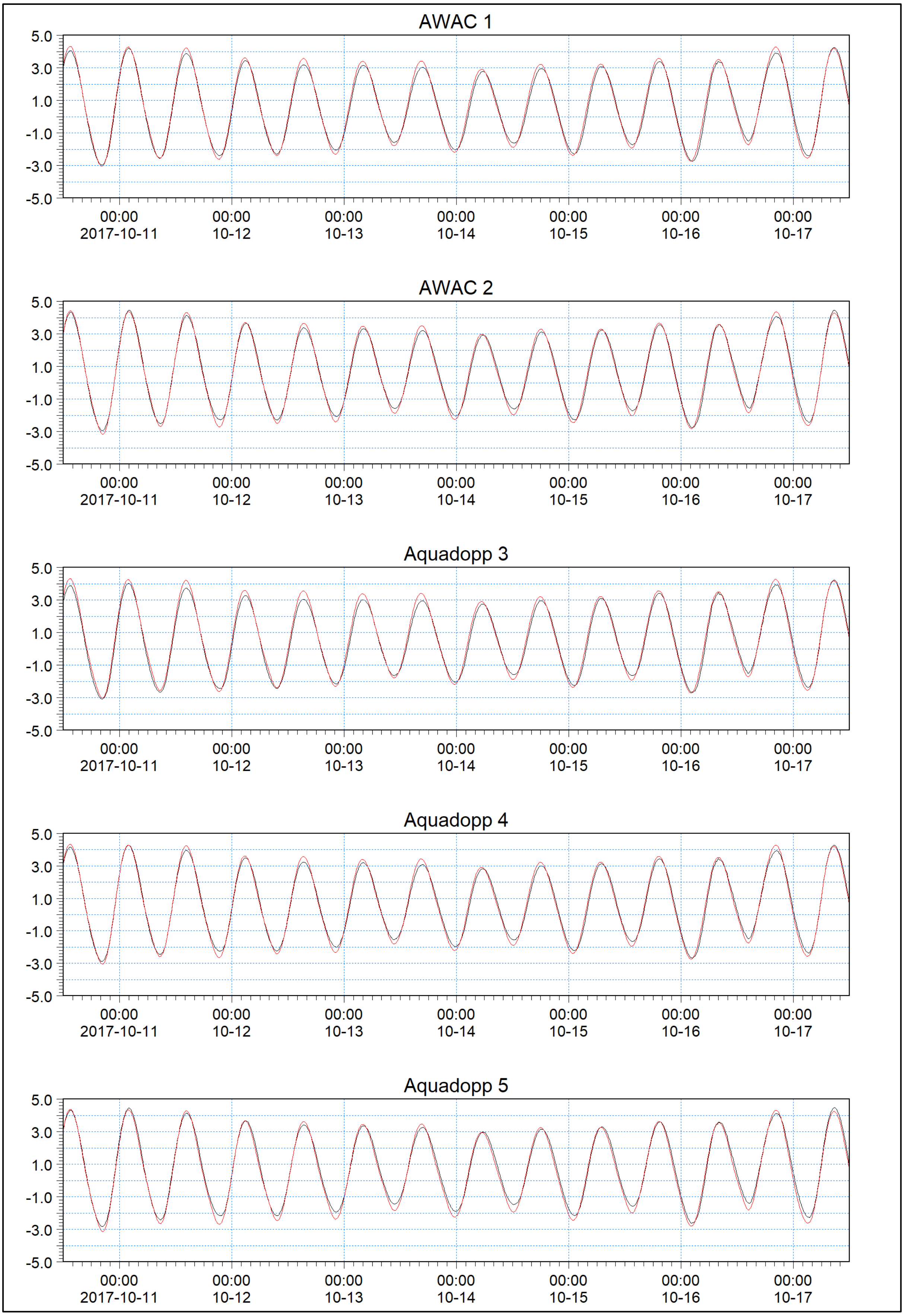


Figure 23. Timeseries comparison of surveyed water levels for validation period (model output in red)

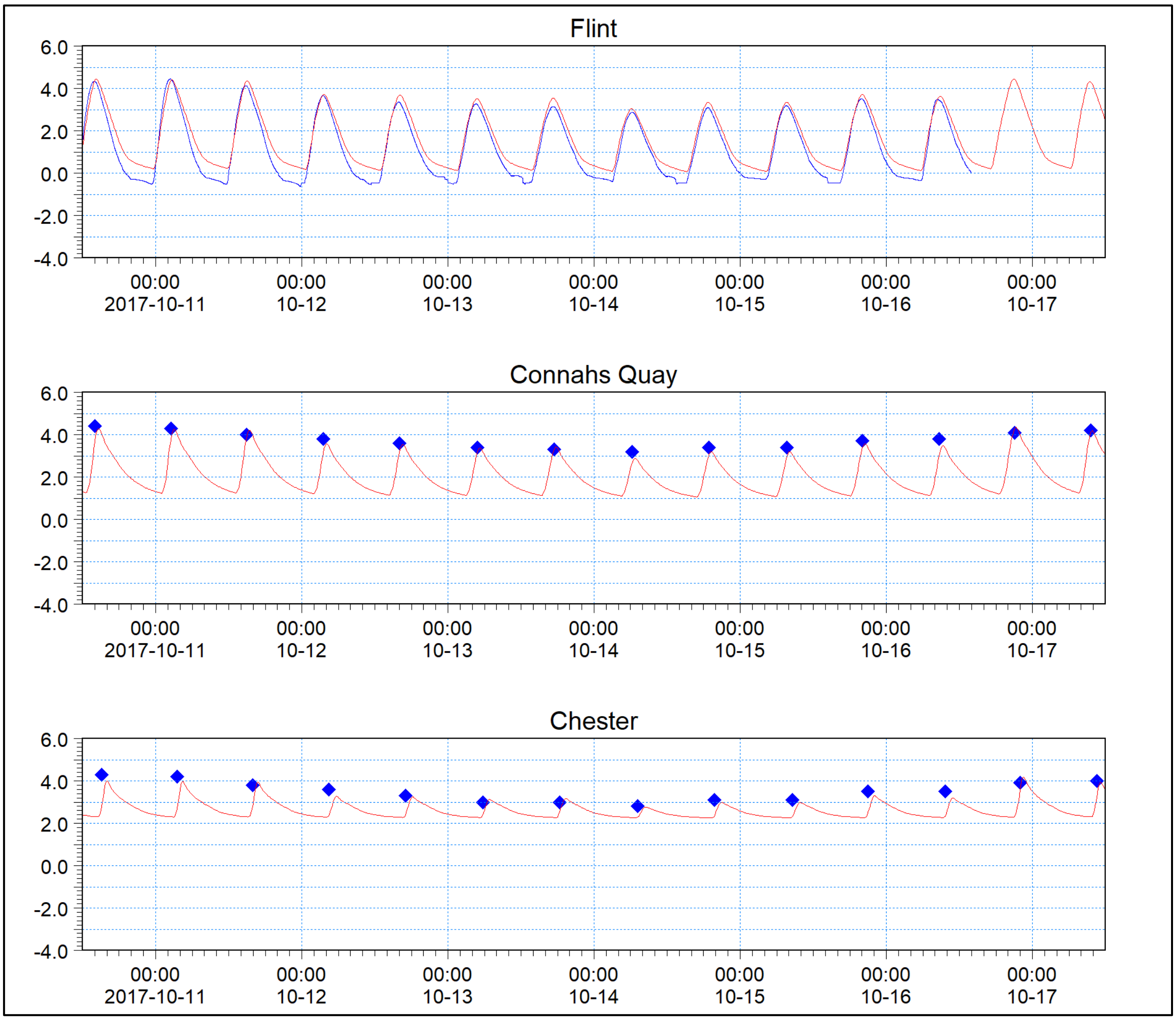


Figure 24. **Timeseries comparison of upstream water levels for validation period (model output in red, predicted HW elevations only for Connah's Quay and Chester)**

When compared against the tide gauge data at Flint, and the tidal predictions upstream at Connah's Quay and Chester, the model continues to perform relatively well, particularly when compared to HW elevations. As with the calibration stage, the tidal predictions at Connah's Quay and Chester do not provide for LW elevations, hence no calibration statistics are available for these parameters at these locations, and the timeseries plots provide a comparison against predicted HW elevations only.

It is further noted that the model boundaries include the effects of meteorological surge (in order to improve the spring tide calibration against the measured data in the primary area of interest). Tidal predictions for Connah's Quay and Chester only provide the astronomic tidal component and, consequently, are not directly comparable to the model output. They do, however, give a useful insight into the tidal propagation, into upstream sections of the model, allowing general HW elevations and phasing to be compared. As seen for the calibration, the accuracy of the model with respect to the phasing reduces in the river section of the model. Overall, the RMS error is less than 0.25 at all sites where this can be measured.

The vast majority of performance metrics are well within the recommended values (identified by the green values in Table 3, indicating the model is performing to an acceptable level of accuracy. Where values fall outside the recommended values, these relate to the absolute bias at some deployment locations, although the relative bias remains within the guidelines when compared to the neap tidal range. At upstream locations, comparison of modelled LW levels against the Flint tide gauge and HW predictions at Connah's Quay and Chester, show similar variance to that observed in the calibration stage, hence the same effects from the bathymetric resolution occur on neaps as they do on spring tides.

Overall, it is considered that the results of the validation exercise confirm that the water levels continue to be well-represented by the numerical model, particularly in the main area of interest in the mouth of the estuary.

3.4.2 Currents

The results of the model validation stage, for currents, are provided below in Figure 25, Figure 26 and Table 6, using the same approach of statistical analysis and timeseries graphical comparison as that applied in the calibration stage (see Section 3.3).

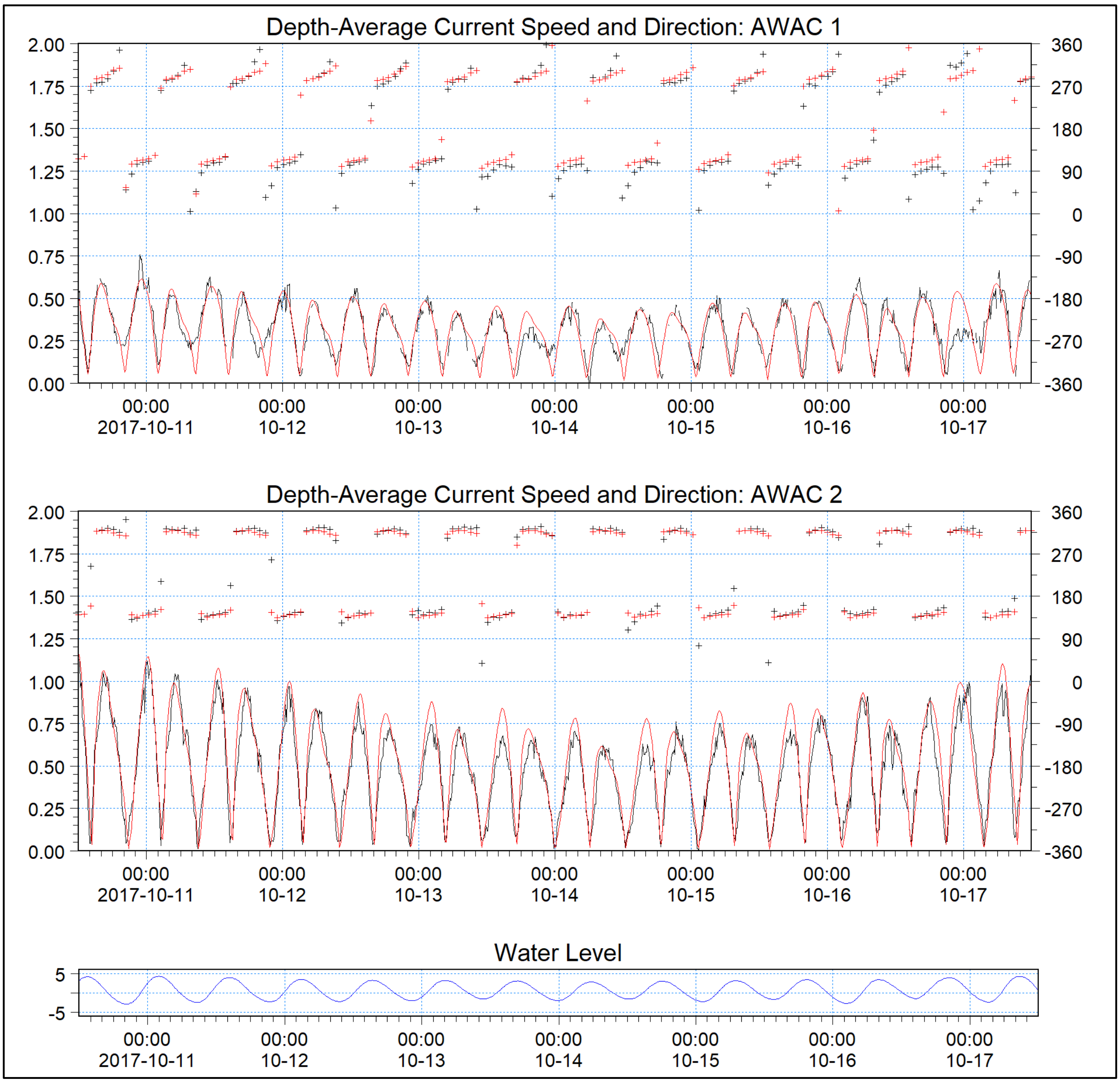


Figure 25. Timeseries comparison of AWAC current speed and direction for validation period (model output in red)

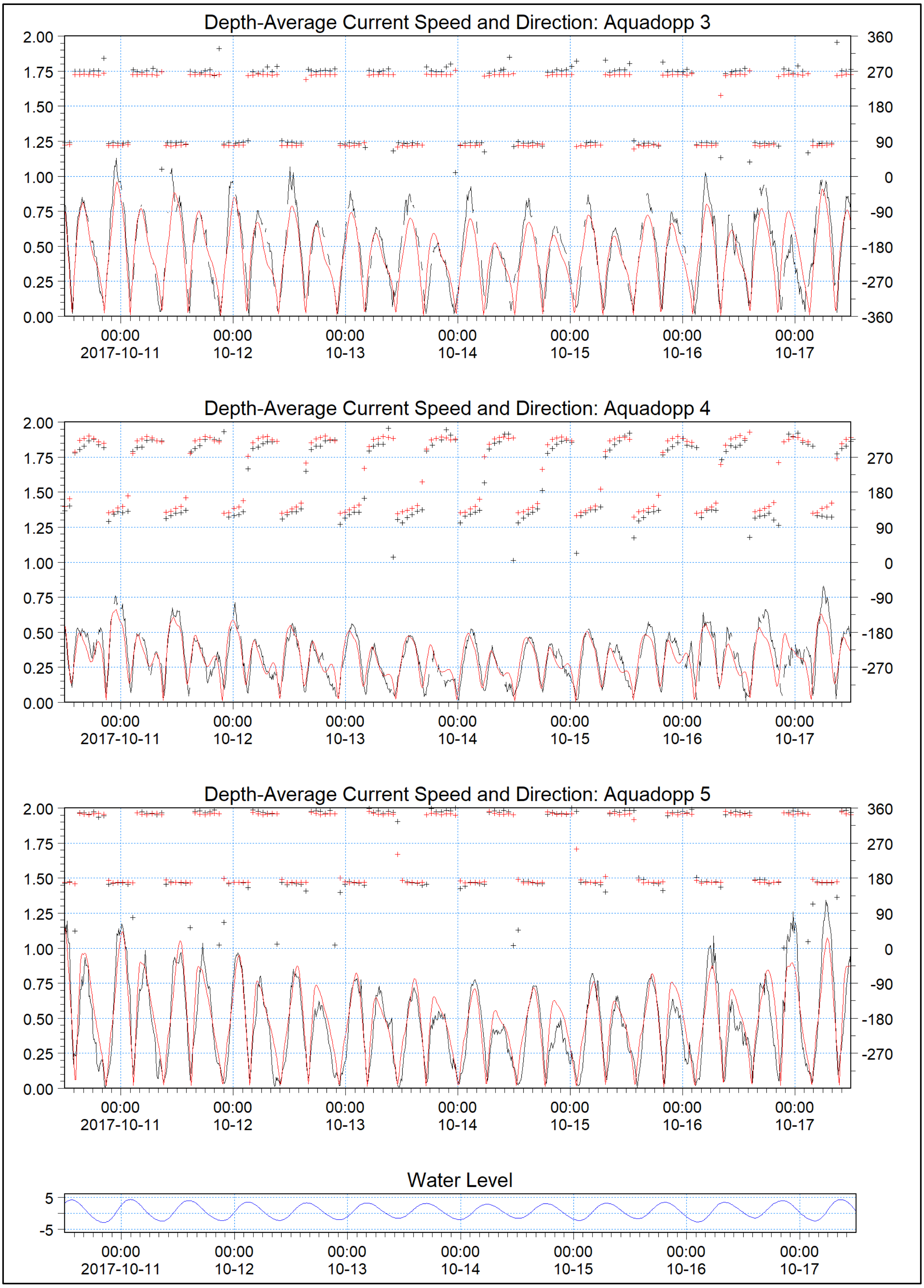


Figure 26. Timeseries comparison of Aquadopp current speed and direction for validation period (model output in red)

Table 6. Current speed and direction validation statistics

Metric	Location				
	AWAC 1	AWAC 2	Aquadopp 3	Aquadopp 4	Aquadopp 5
Mean Ebb speed diff (% peak)	2.8	1.1	-2.4	-2.4	-0.2
Mean Flood speed diff (% peak)	-6.5	7.1	-15.1	-8.2	-2.6
Mean Ebb direction diff (°)	1.9	-2.7	-8.4	15.9	-4.6
Mean Flood direction diff (°)	8.1	-2.5	-6.5	10.6	-0.3
RMS Error	0.11	0.10	0.18	0.10	0.12
Green Indicates value is within calibration guidance recommended values; Orange Indicates value is outside.					

It can be seen from the timeseries comparison, and the associated statistical analysis, that the model is performing well in representing currents (both speeds and directions) throughout the study area. The bias between the model and the measured survey data remains well within ±20% of peak values on both the flood and ebb stages, with almost all locations showing levels well within ±10% of peaks. The majority of sites reveal that peak flow directions are well within the ± 15° guidance limit; whilst the RMS error is less than 0.2 at all sites.

The one occurrence of the calibration guidance statistics not being met is shown when comparing the model ebb flow direction at Aquadopp 4 (located within Mid Hoyle Channel, see Figure 10). At this site, the modelled ebb directions are shown to be aligned slightly more clockwise (towards the north), than the measured data (as evident in Figure 14). As noted in the calibration stage, it is possible that the channel alignment has shifted between the survey (carried out in August 2017, and which provided the bathymetry data for this section of the model), and the survey deployment during October 2017. Nevertheless, the model performance (a shift of 15.9°) remains generally aligned with the performance guidelines (which state directions should be replicated to within ±15°).

Overall, it is considered that the results of the validation exercise confirm that the depth-averaged flow conditions are well-represented by the numerical model, with respect to tidal propagation of water levels, flow speeds and directions through the main estuary channel system.

As with the spring tide calibration the model clearly replicates the near rectilinear flows throughout the flood and ebb tide in the Welsh and Hilbre Channels. In the Mid-Hoyle Channel, outer (AWAC 1) and inner (AWAC 2) locations, the observed rotation effects on the flows are modelled with the correct rotational speed, which varies between the sites.

Comparison against other intertidal ADCP transect data

As described in Section 3.2.5, the reported results from the cross-shore intertidal ADCP transects, collected for the Mostyn Energy Park proposal (HRW, 2012) were also reviewed. These results were used to compare against the model output over equivalent range tides. This comparison shows that the model generally compares favourably with the measured data. The measured data along the outer extent of the transects (close to the lower limit of the intertidal), describes peak depth-averaged spring current speeds ranging from around 0.25 m/s close to the Port of Mostyn, to approximately 0.44 m/s towards the Point of Ayr. Equivalent values on neap tides range from around 0.21 to 0.28 m/s. By comparison, the equivalent modelled current speeds range from 0.25 to 0.41 m/s on spring tides and 0.16 to 0.24 m/s on neaps.

It should be noted that this only provides a semi-quantitative comparison of flow characteristics, over generally approximate tidal ranges. The model run period and the ADCP deployment period do not coincide, thus any influence from meteorological forcing (for example) will not be comparable between the two datasets. The comparison does, however, show that the peak modelled current speeds, across the Mostyn Bank area, are generally consistent with available measured data.

3.5 Wave model verification

The principal aim of the present assessment is to examine how waves within the Dee Estuary and approaches may be affected by the development, which is to be assessed by examining extreme wave conditions at the site. 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 survey deployment. The location of the AWAC deployments is shown in Figure 10

The verification period includes a number of events that were recorded by the AWAC devices. 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.

The model was then run with varying waters levels extracted from the hydrodynamic model simulation for the same period (see above). 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.

The results of these verification simulations are presented in Figure 27, with further comparison provided in Figure 28. 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 in and around the Port of Mostyn or approaches.

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

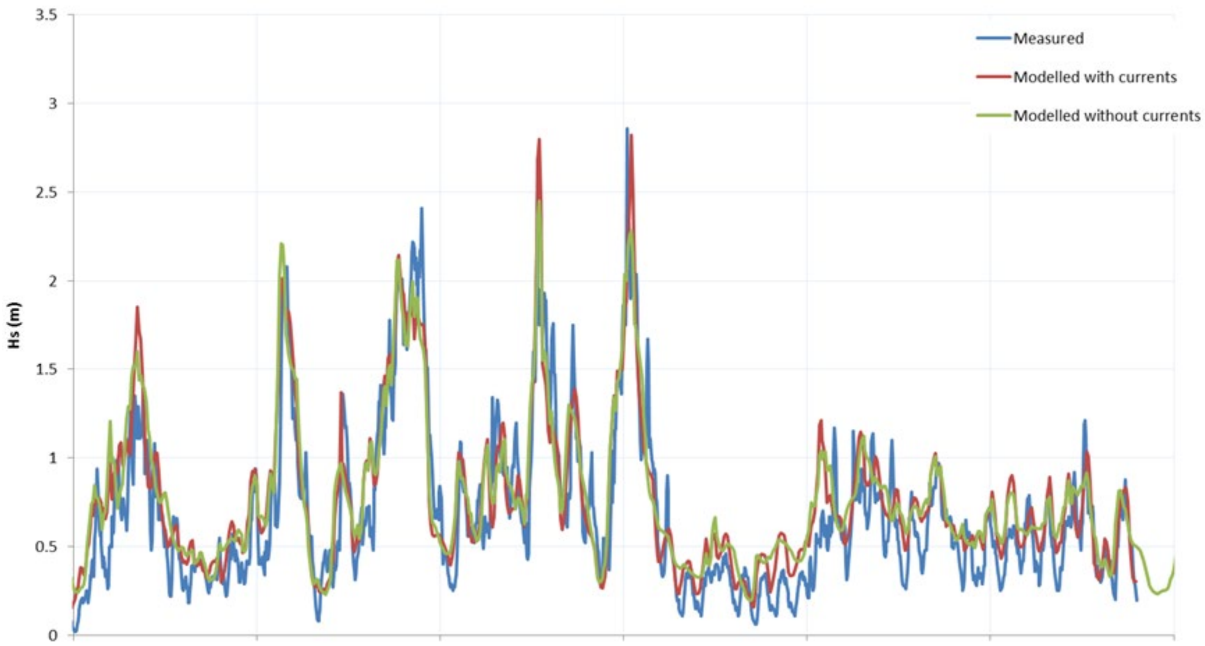


Figure 27. Verification of significant wave height (with and without modelling of wave-current interaction)

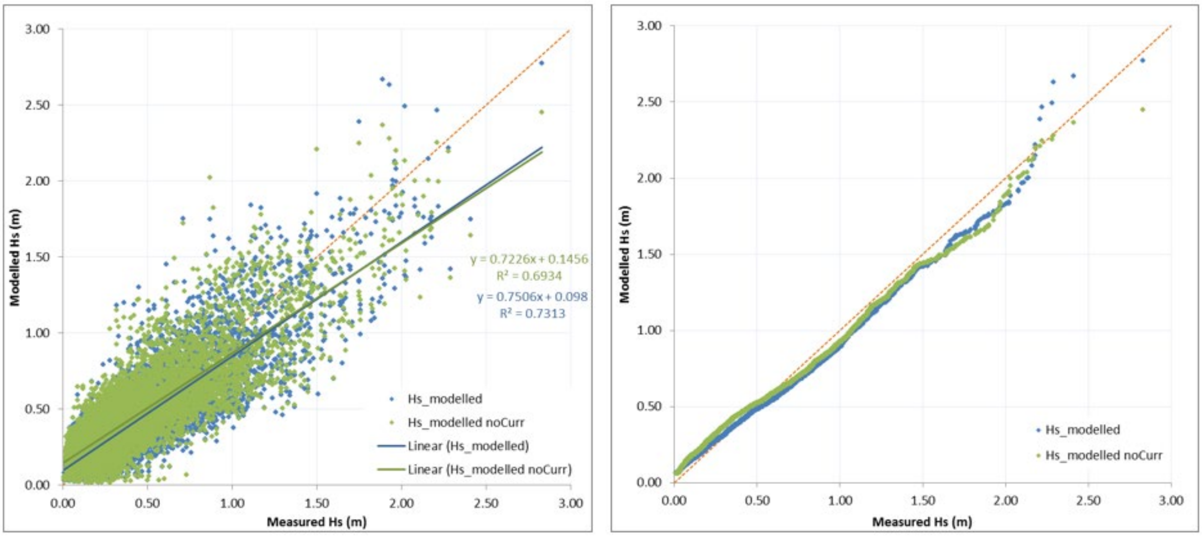


Figure 28. Scatter and Q-Q plots comparing wave odel influence of wave-current interaction

4 Conclusion

Comparison of the modelled and measured water levels along with the model performance metrics show that overall the model performs well in replicating the water levels throughout the tide and the propagation through the estuary. The model accuracy is slightly lower in the confined river section than in the main area of interest at the mouth of the estuary and around the Port of Mostyn. The validation exercise suggests that the model produces a slightly larger tidal range (higher HW and lower LW) than measured at the deployment sites within the field survey and the tide gauge predictions.

The timeseries and statistical metrics for flow speeds and directions at the five point locations are, for the most part, well within what is considered a good calibration. Visual inspection of the comparisons also shows the variation between sites of the rectilinear and rotational flows is replicated along with the flood/ebb asymmetry and semi-diurnal differences.

Comparison of ADCP-measured flow speed/direction transects with the model flow distribution results show good agreement, indicating that the model is performing well across the main channels.

Overall, it is concluded that the model performs well at replicating the hydrodynamics presently occurring within the Dee Estuary and in the area around the Port of Mostyn. The model is, therefore, considered to be an accurate tool to assess the potential effects of the proposed MEPE scheme. This will also provide information to allow the EIA studies to assess the likely physical processes (and other topics, such as ecology) impacts of the scheme. The model will not directly provide information on the long-term evolutionary effects but will identify areas of the estuary where the forcing parameters might significantly change.

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6 Abbreviations/Acronyms

2D	Two-Dimension(al)
ADCP	Acoustic Doppler Current Profiler
ArcGIS	Geographic Information System Mapping Tool
AWAC	Acoustic Wave and Current Meter
BNG	British National Grid
CFSv2	Climate Forecast System v2
CTD	Conductivity, Temperature and Depth Probe
DCO	Development Consent Order
DHI	Danish Hydraulic Institute
diff	Difference
DTM	Digital Terrain Model
EMODnet	European MARINE Observation and Data Network
FM	Flexible Mesh
GEBCO	General Bathymetric Chart of the Oceans
HD	Hydrodynamic
HW	High water
LiDAR	Light Detection And Ranging
LW	Low Water
MEPE	Mostyn Energy Park Extension
NA	Not Applicable
NRW	Natural Resources Wales
NSIP	Nationally Significant Infrastructure Project
NTSLF	National Tidal and Sea Level Facility
ODN	Ordnance Datum Newlyn
PINS	Planning Inspectorate
RM	Rectilinear Mesh
RMS	Root Mean Square
RMSE	Root-Mean-Square Error
SMP	Shoreline Management Partnership
UKHO	United Kingdom Hydrographic Society
WL	Water Level

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

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