Blackwater and Colne Estuaries - Hydrodynamics Model Validation

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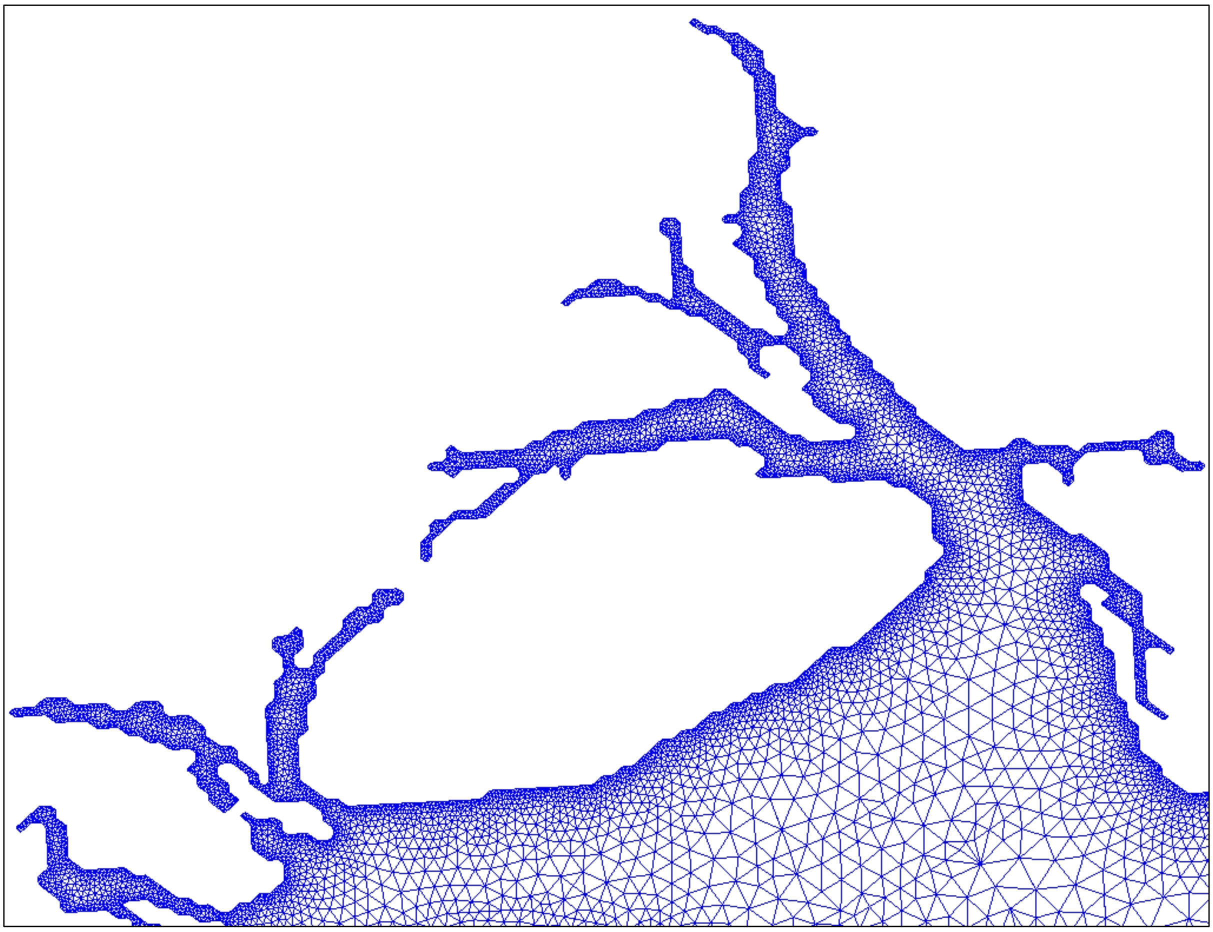

Executive Summary

A three-dimensional hydrodynamic (HD) model of Blackwater and Colne estuaries on the Essex coast has been constructed using the open-source Telemac code [TELEMAC, 2024]. The 3D model extends from Walton-on-the-Naze in the north-east to Shoeburyness in the south-west and spans the waters of the Blackwater, Crouch, Roach and Colne estuaries Marine Conservation Zone (MCZ). This report focuses on the validation of the model against physical observations across the region.

The tidally-driven oceanography in the area depicts a complex water circulation system, displaying various levels of density stratification and atmosphere-water heat exchange throughout the year. For the 3D model, a non-hydrostatic approach is used to explicitly solve for vertical currents. Freshwater inputs from the main river sources were included to account for salinity and temperature differences that can act as an important driving force for fluid movement.

Based on the time of year of the study, meteorological wind forcing on the water surface was included. The model also incorporated the Coriolis force due to the Earth's spin and sea-bed friction. Validation of the model against observed hydrographic data (water levels and currents), at locations across the area, used data lifted from the United Kingdom Hydrographic Office (UKHO) Admiralty Total Tide (ATT) package [ATT, 2024].

Tidal propagation over the Essex coast MCZ region is correctly simulated, and its 3D approach reasonably describes flow currents in terms of magnitude and direction. Model predictions generally satisfy specific calibration/validation requirements for hydrodynamic and discharge modelling [SEPA, 2019] [FWR, 1993] and compare favourably with similar previous work [FRC, 2009]. Python scripts have been developed to directly compare observed and modelled data within the open-source platform CLAWS – Chemicals for Lice and Waste from Salmon Farms [CLAWS, 2024].

General insight into the spatial and temporal variations in the flow environment in the MCZ is provided by the model. It offers a suitable basis for assessing near-field and far-field dispersion effects of particulate matter such as oyster larvae, Escherichia coli (E. coli), nutrients and plastic waste.

About the Report Authors

***Dr Tom Scanlon** BEng PhD CEng MIMechE, Engineering Consultant, MTS-CFD.com*

Tom is a chartered professional engineer with over 25 years' experience in applied computational mechanics. After a first degree in Environmental Engineering at the University of Strathclyde, Tom undertook a Ph.D in Vortex Shedding Flowmeter Pulsating Flow Computational Fluid Dynamics (CFD) Studies at the same university. Subsequently, he was awarded a JM Lessels scholarship from the Royal Society of Edinburgh for a one-year post-doctoral position at the Institute de Mécanique des Fluides de Toulouse, France in the field of numerical oceanography. The IMechE presented Tom with the Alfred Rosling Bennett Premium and Charles S Lake Award in 2003 for CFD in applied aerodynamics. In 2013 Tom returned from an EPSRC-funded sabbatical in the USA, where he carried out fundamental research in rarefied gas dynamics at the University of Michigan and the Lawrence Berkeley Laboratory in California. From 1994-2017 he was a Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the University of Strathclyde specialising in heat transfer, fluid mechanics and applied CFD. His work is reported in over 50 refereed journal and conference publications. He is currently a director at the engineering consultancy firm MTS-CFD.

***Dr Matt Stickland** BSc PhD CEng FIMechE, Engineering Consultant, MTS-CFD.com*

After a first degree in Aeronautical Engineering at the University of Manchester, Matt worked for BAE Systems (Military Aircraft) at Warton in Lancashire in the Wind Tunnel Department working on projects which included EAP, EFA (Typhoon), Tornado and HOTOL. After leaving BAE in 1990 Matt worked for YARD Consulting Engineers in Glasgow modelling the heat and fluid flows in Advanced Gas Cooled reactors during on-load refuelling. In 1991 Matt accepted a senior lectureship in the Department of Mechanical Engineering at the University of Strathclyde where his research interest covered both experimental and computational heat transfer and fluid dynamics. He was awarded a PhD for his research into 3D imaging and its application to fluid flow visualisation. For his research in the field of experimental and computational fluid dynamics he was awarded the 2003 AR Bennett Premium/CS Lake Award and the 2004 T A Stewart-Dyer Prize/Frederick Harvey Trevithick Prize from the Institute of Mechanical Engineers. In 2022 Matt left the University of Strathclyde to take a directorship with the Engineering consultancy firm MTS-CFD. Matt is a Chartered Engineer and a Fellow of the Institute of Mechanical Engineers. He has published his research in over 100 papers in refereed journal and conference proceedings.

1 Introduction and Motivation

This report has been prepared by engineering consultants MTS-CFD, as part of hydrodynamic modelling services to consider the dispersion of particulate matter such as oyster larvae, E.coli, nutrients and plastic waste in the Blackwater, Crouch, Roach and Colne estuaries Marine Conservation Zone (MCZ) on the Essex coast. Modelling of the particulate matter is reported elsewhere and this report focuses on the hydrodynamics validation.

The report describes the development and validation of a 3D hydrodynamic model to capture adequately the current patterns in the MCZ.

A 3D hydrodynamics approach based on the open-source Telemac code [TELEMAC, 2024] has been employed. The hydrodynamic model contains the influence of weather forcing and stratification through the salinity and temperature fields.

As part of the hydrodynamics development work, new Python scripts have been written to allow the user to compare directly modelled and observed data. These data are output in a format that quickly allows the user to assess how well the model data compares against physical observations.

2 Model Development

2.1 *Hydrodynamics*

The modelling approach employed the 3D non-hydrostatic version of the open-source hydrodynamics code Telemac [TELEMAC, 2024] across the MCZ, the extent of which is shown in Figures 1-4. To model depth, 10 terrain-following vertical sigma layers are applied and the model includes tidal and wind forcing, stratification due to freshwater inflows and atmosphere-water heat exchange. Approximately 0.5 million elements were used in the model and it extends from Walton-on-the-Naze in the north-east to Shoeburyness in the south-west and spans the waters of the Blackwater, Crouch, Roach and Colne estuaries.

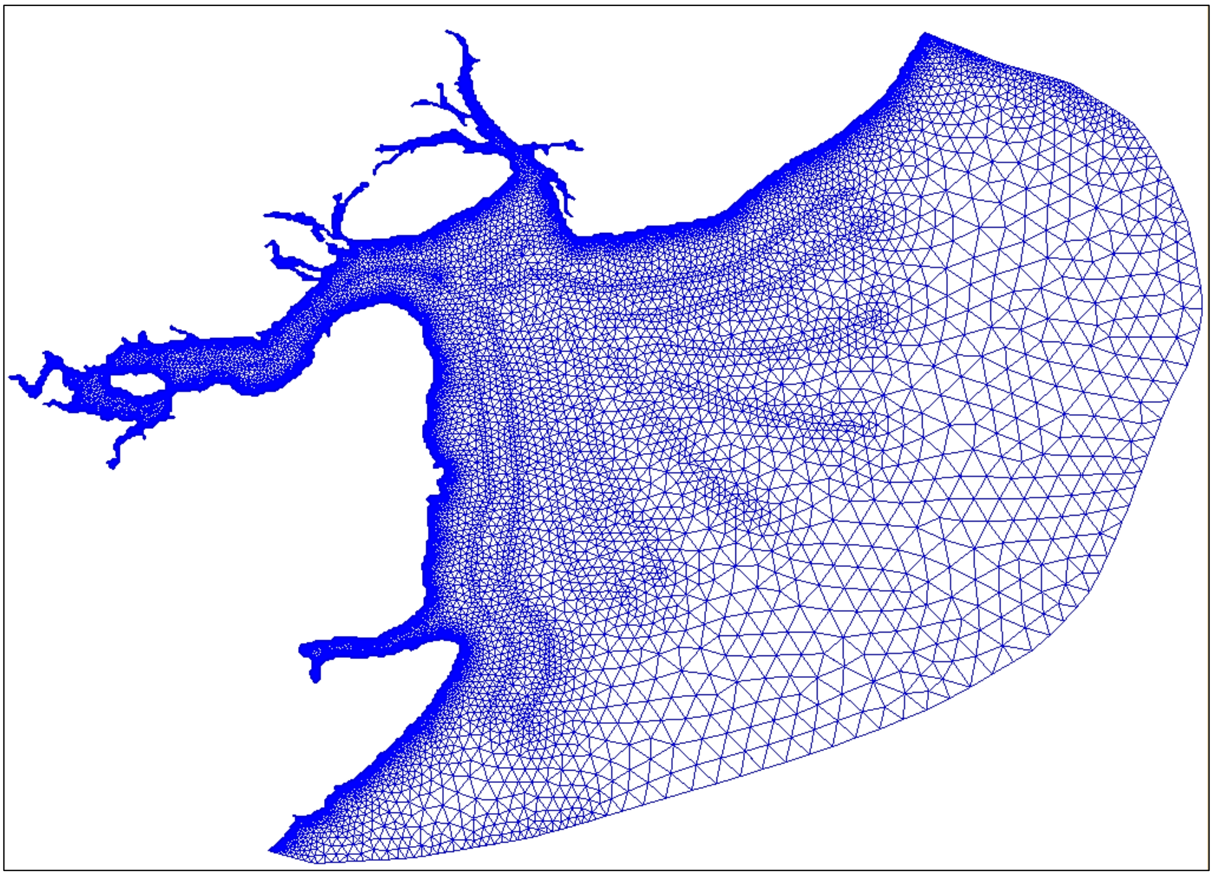

Figure 1 *Telemac 3D hydrodynamic mesh and model extent.*

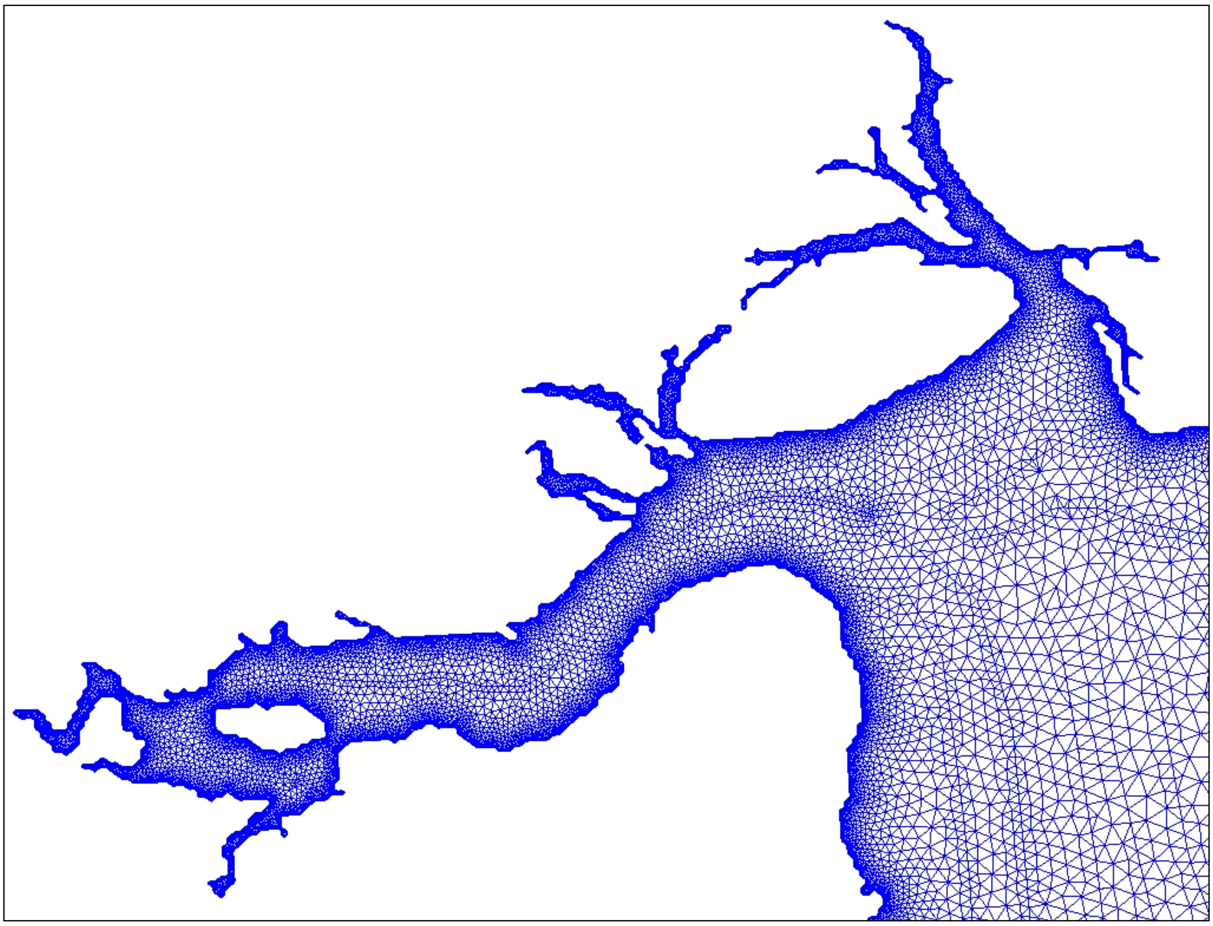

Figure 2 *Telemac 3D hydrodynamic mesh (zoomed).*

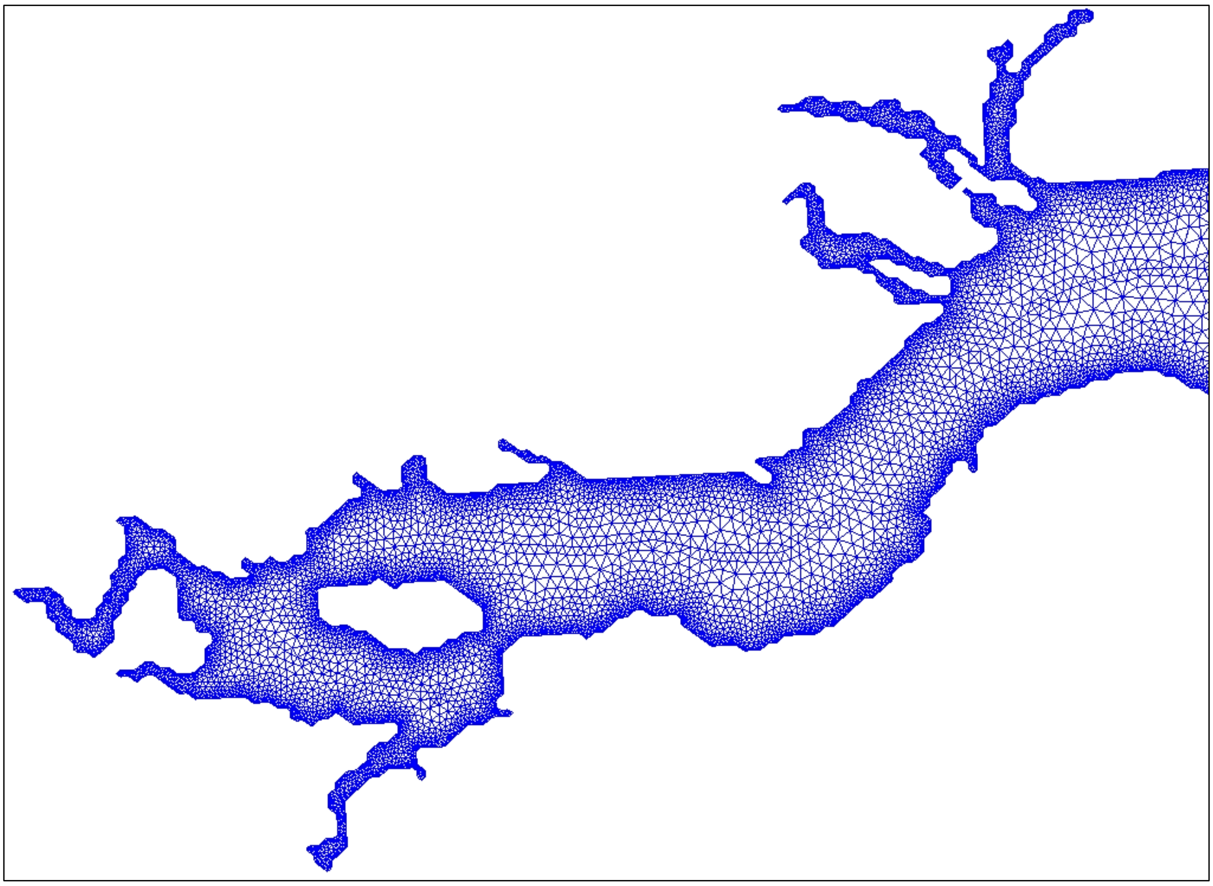

Figure 3 *Telemac 3D hydrodynamic mesh focused on the Blackwater estuary.*

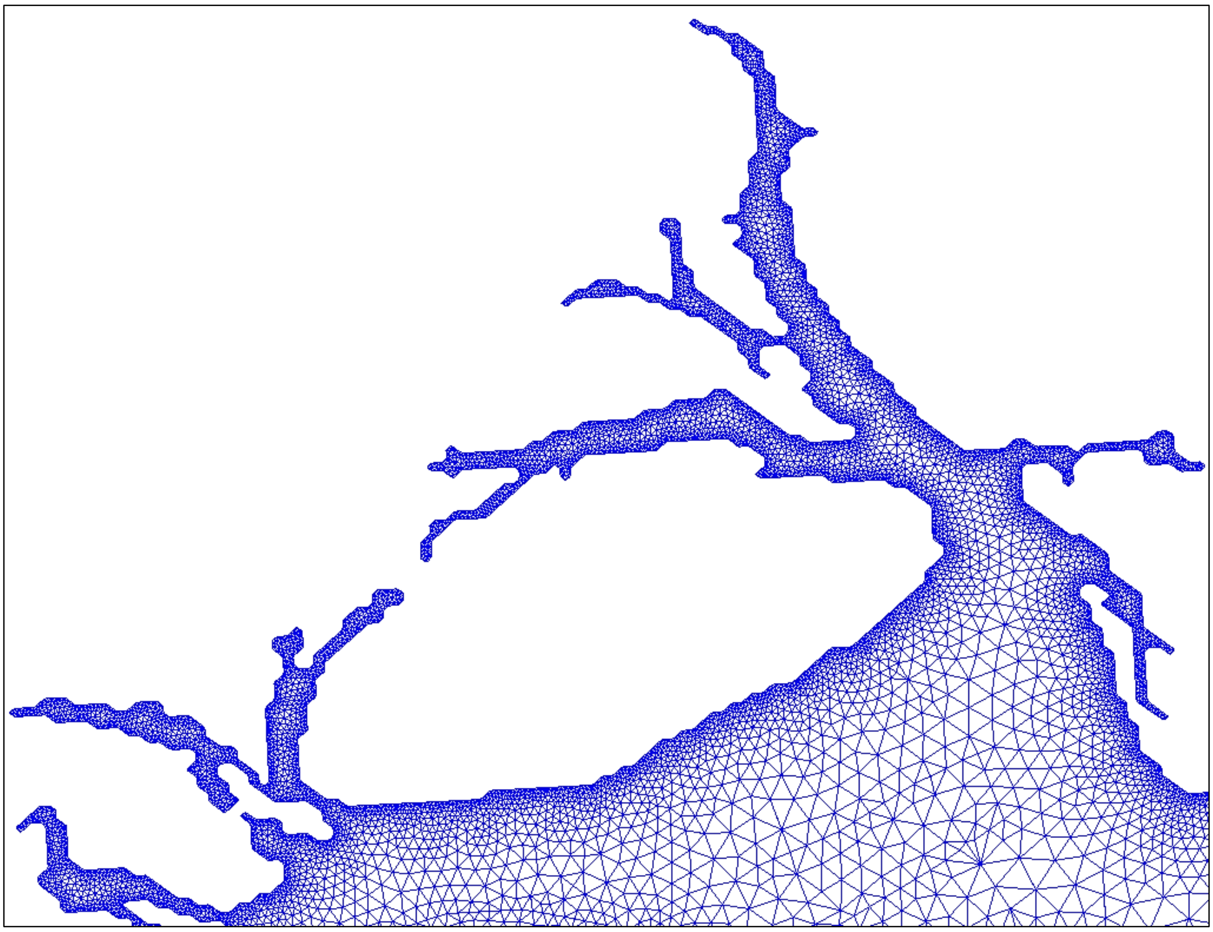

Figure 4 *Telemac 3D hydrodynamic mesh focused on the Colne estuary.*

2.2 *Freshwater Inputs*

Freshwater discharges considered appropriate for the model were considered from the rivers Blackwater and Colne. The flow rates, taken from [NRFA, 2024], were 1.06 m^3/s and 1.38 m^3/s for the Blackwater and Colne, respectively. Values of 0 PSU for salinity and temperature of 15 ^oC were employed as the river inlet conditions.

2.3 *Bathymetry data*

The bathymetry data for the hydrodynamic model have been collected from a range of different sources including publicly available data sets [GEBCO_2024] and digitised Admiralty charts [ADMIRALTY, 2024]. The sea bed depth in the area is shown in Figures 5.

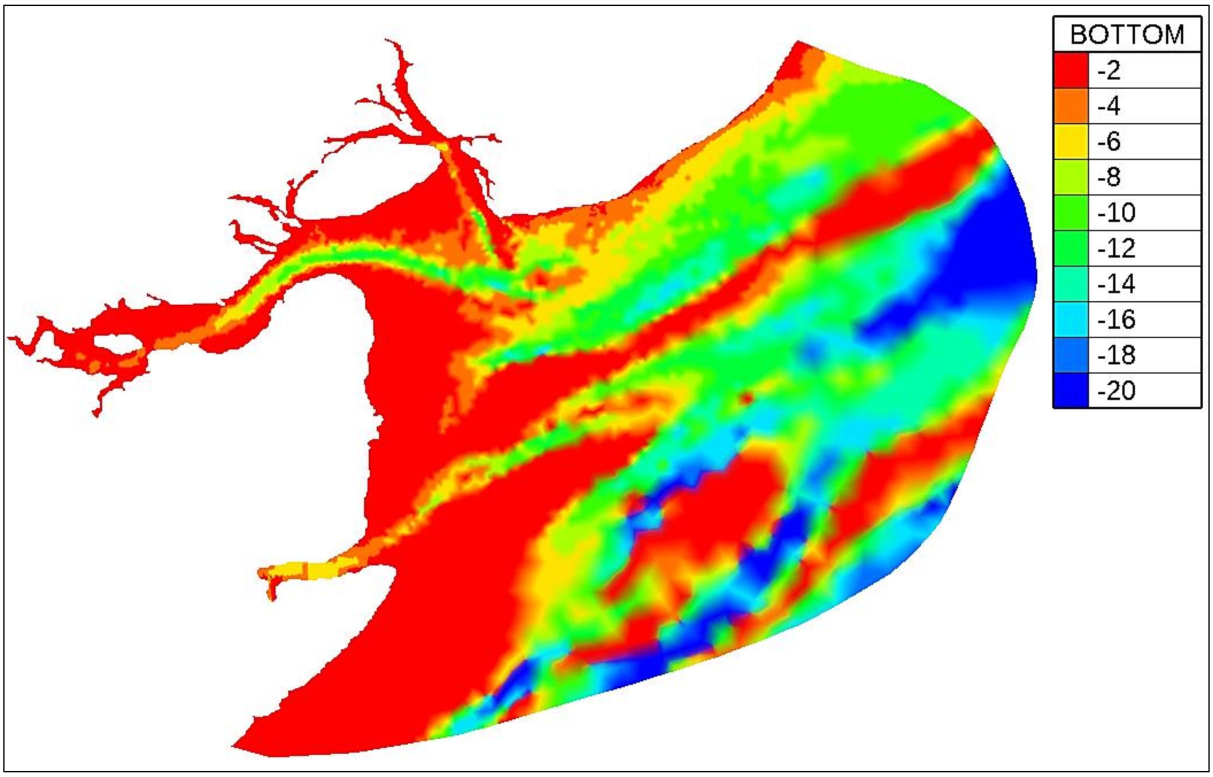

Figure 5 *Sea bed depth (m) across the MCZ model area.*

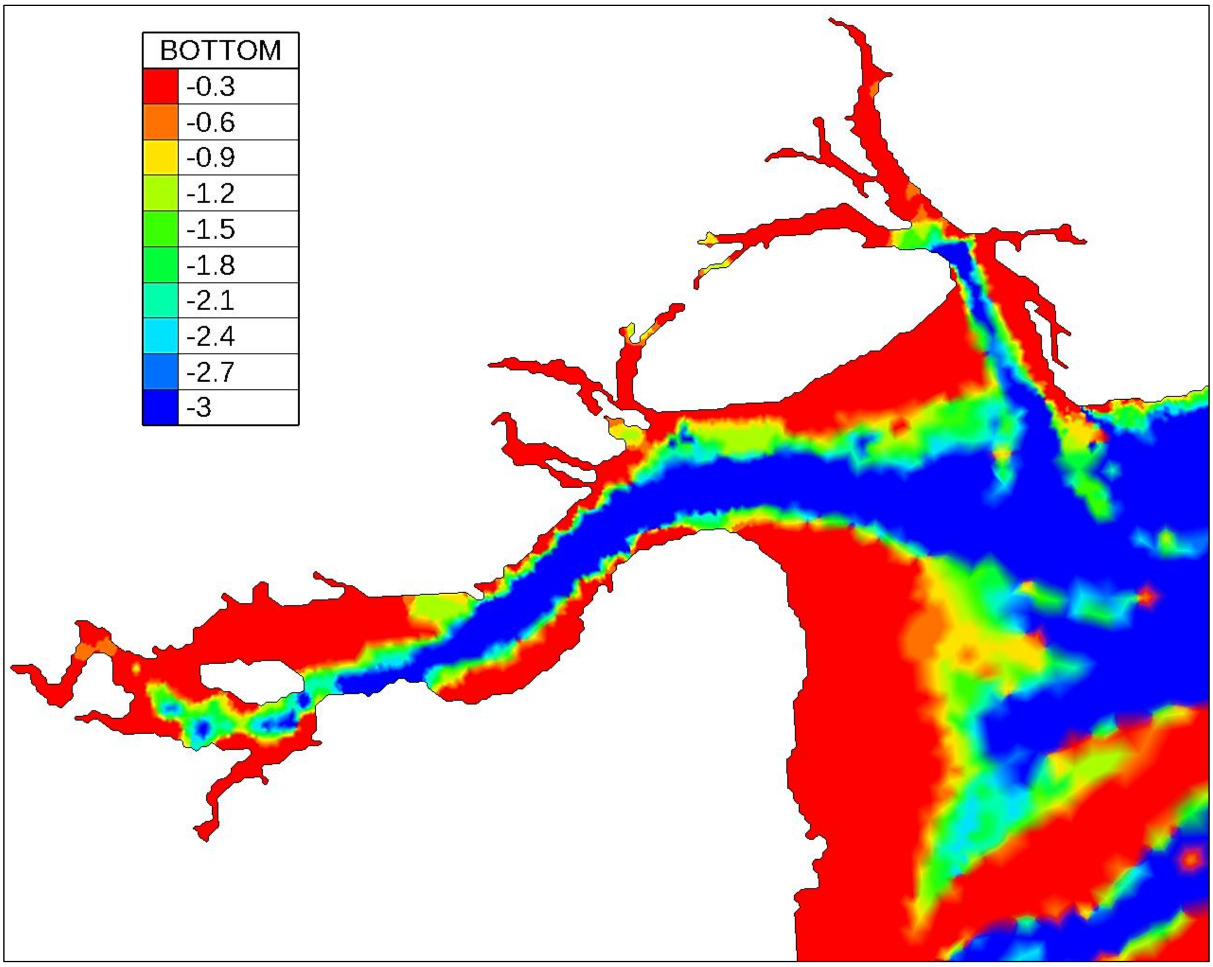

Figure 6 *Sea bed depth (m) focused on the Blackwater and Colne estuaries.*

2.4 *Meteorology*

Wind forcing on the water surface is included in the hydrodynamic model based on weather data at 6-hourly intervals covering the period of the runs [TIME_DATE_2024]. Atmospheric air-water heat exchange is also included in the model in order to resolve the estuary temperature fields.

2.5 *Hydrodynamic runs*

The model was "spun-up" for 4 days (1st - 5th June 2023) to develop the heat and salt fields and the model state at the end of the spin-up period was saved. The main simulations were "hot-started" from this stored field and run across the 14-day period 5th – 19th June 2023.

Figures 7 and 8 show snapshots of the developed salinity and temperature fields, respectively.

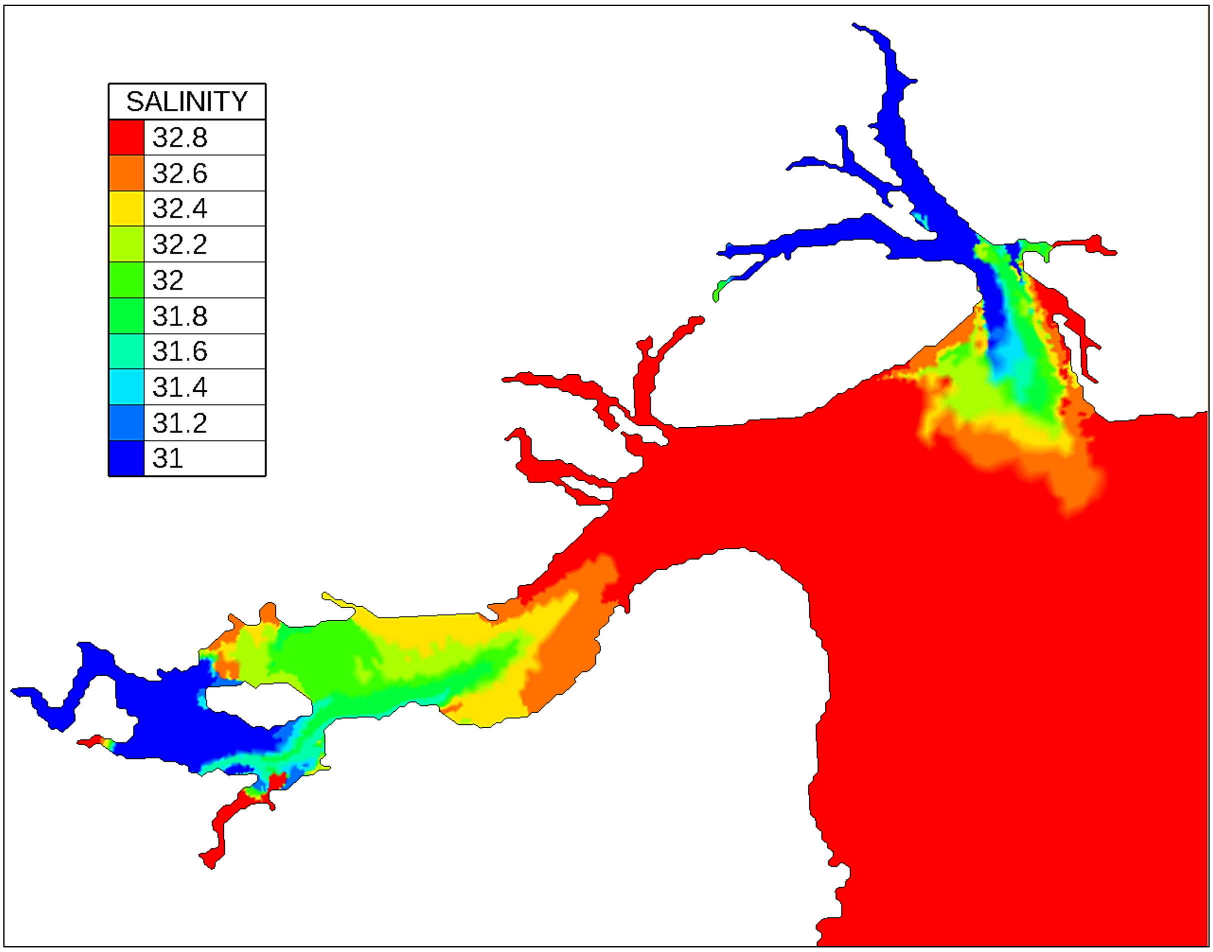

Figure 7 *Snapshot of near-surface salinity (PSU) at 8 a.m. on the 13th June 2023.*

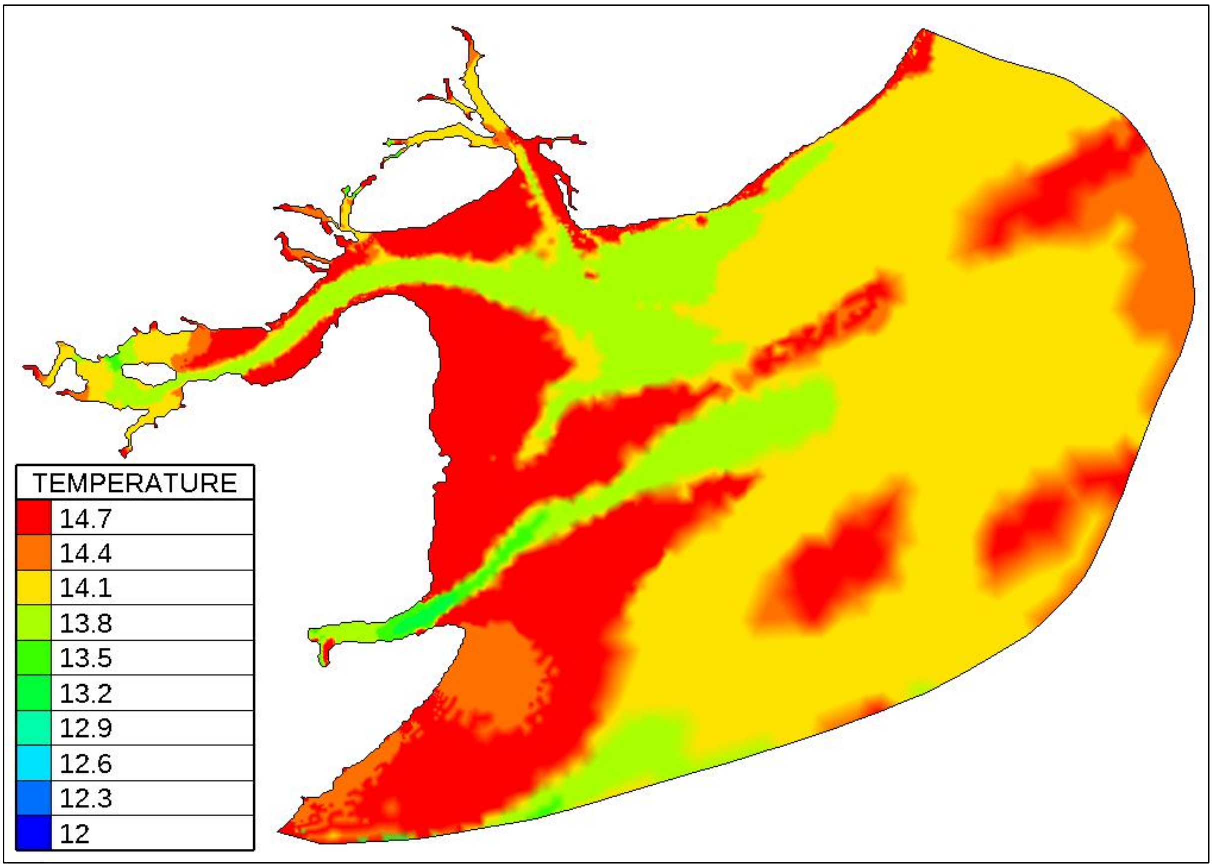

Figure 8 *Snapshot of near-surface temperature (^{o}C) at 1 p.m. on the 6th June 2023.*

2.6 *Flow fields*

Figures 9-12 show snapshots of near-surface flow patterns in the region during flood and ebb tides. These highlight the complexity of the flows due to the competing effects of tides, wind and stratification.

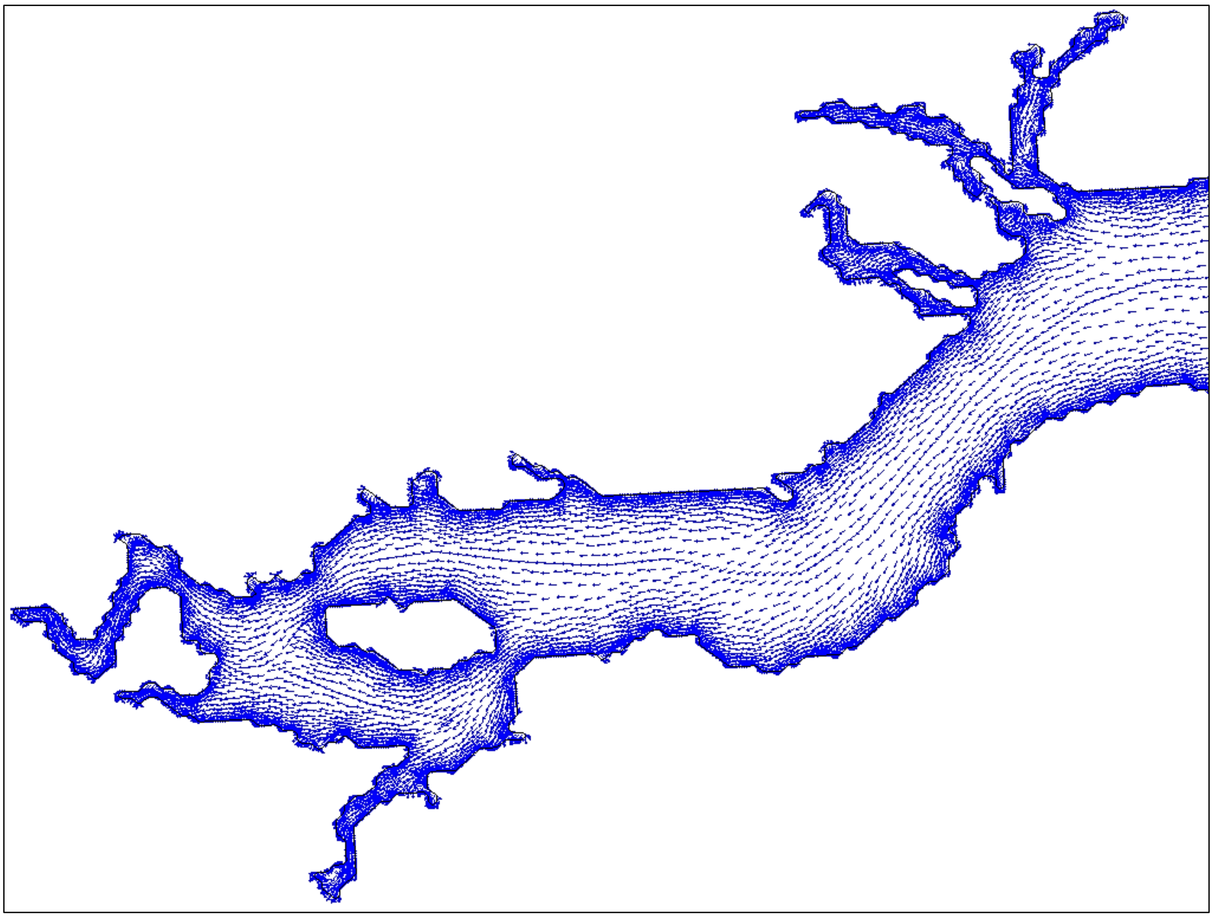

Figure 9 *Snapshot of surface flow patterns on a flood tide in the Blackwater estuary region.*

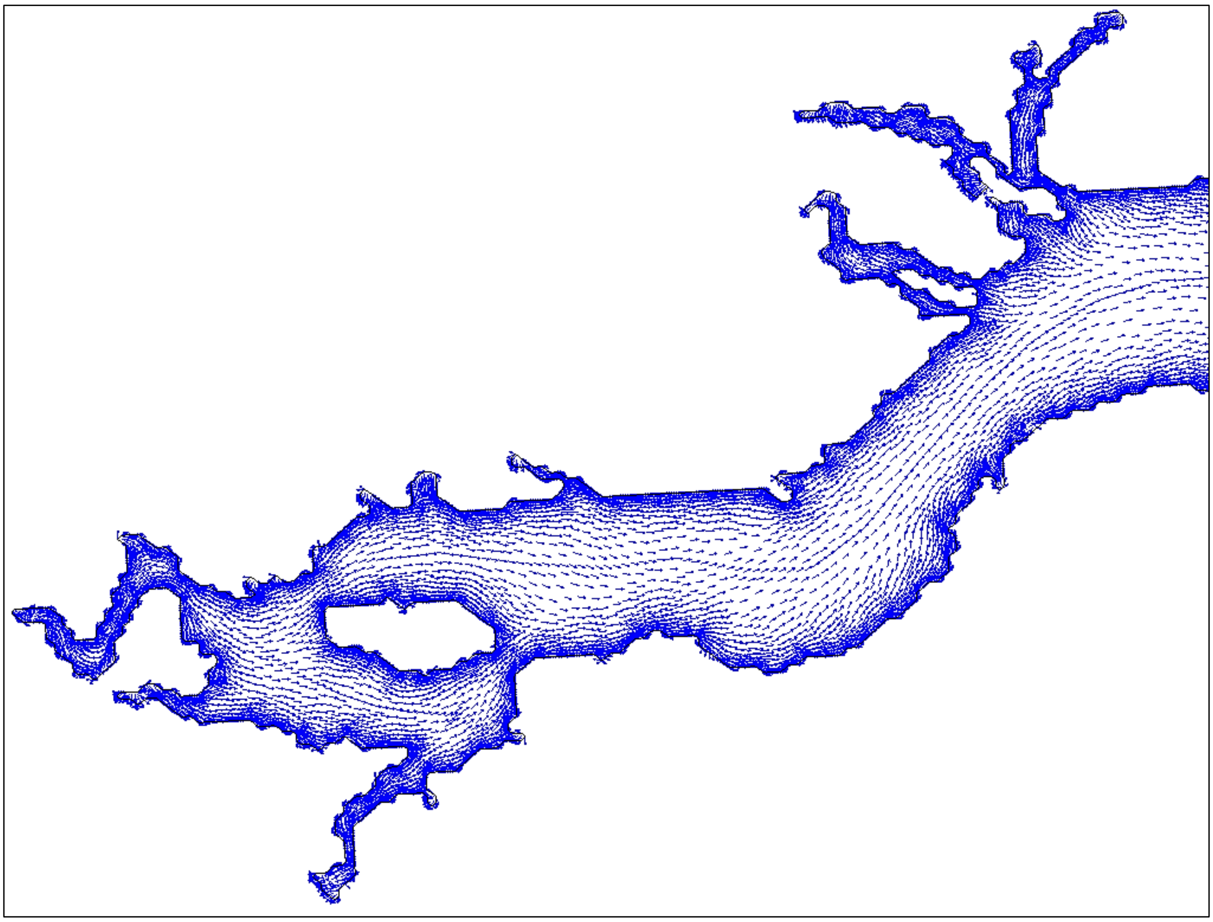

Figure 10 *Snapshot of surface flow patterns on an ebb tide in the Blackwater estuary region.*

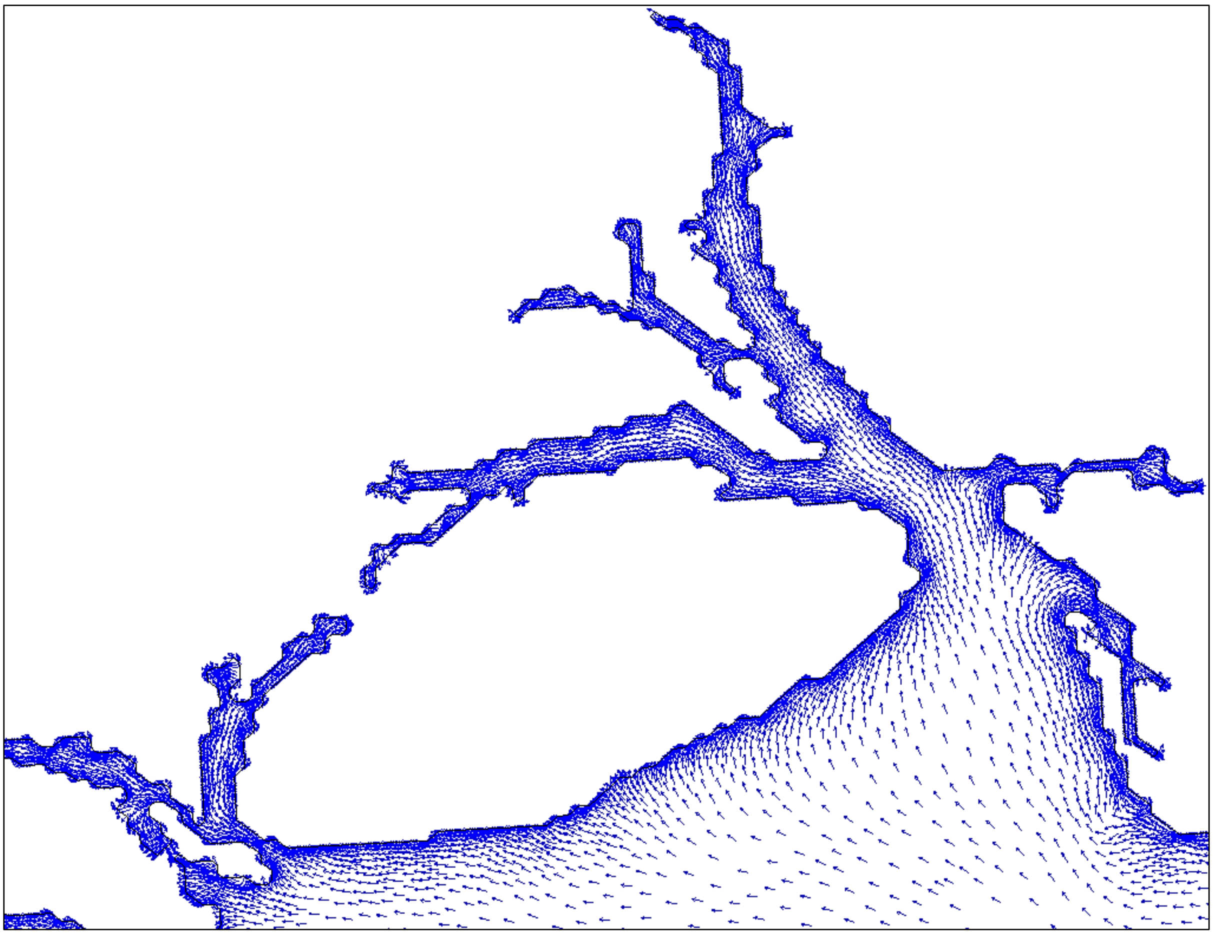

Figure 11 *Snapshot of surface flow patterns on a flood tide in the Colne estuary region.*

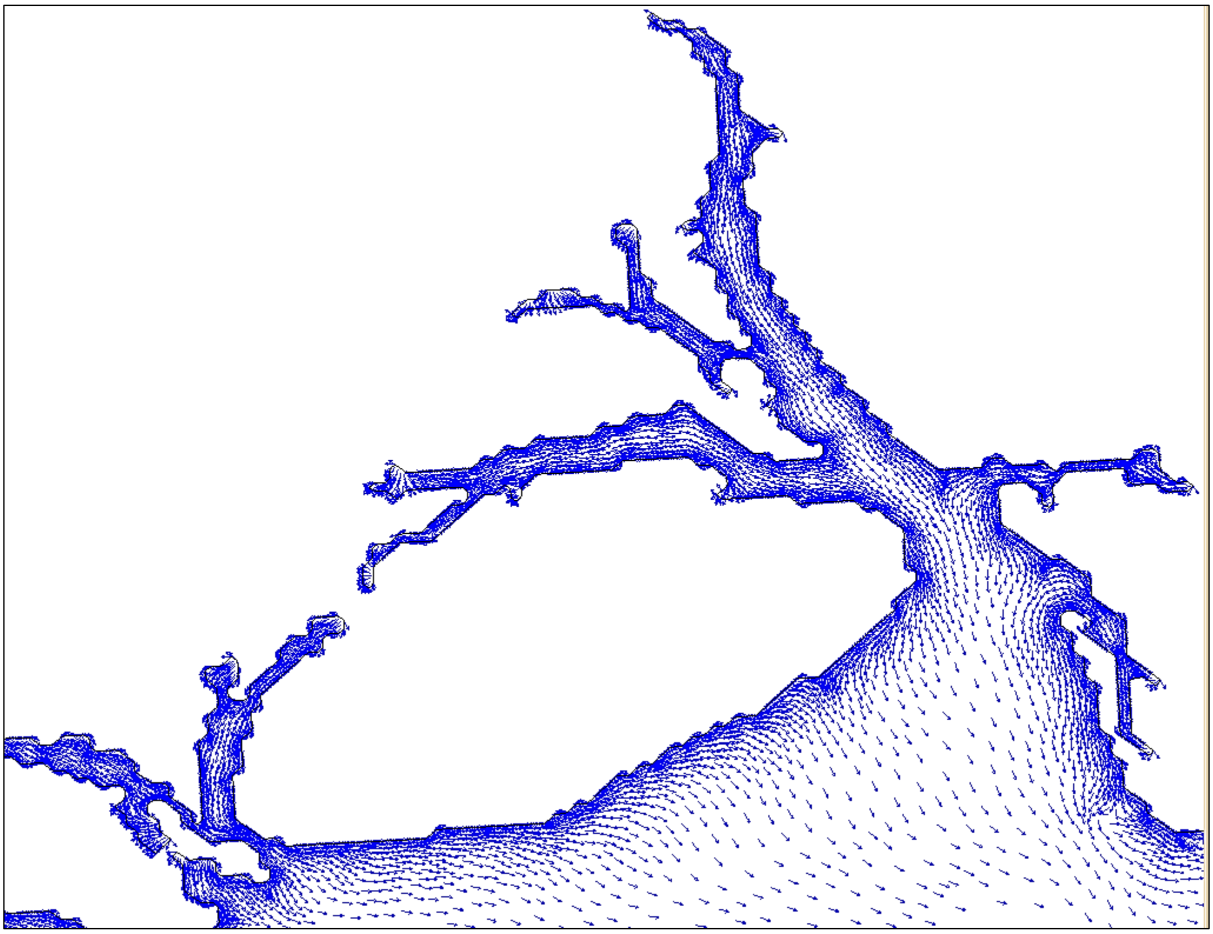

Figure 12 *Snapshot of surface flow patterns on an ebb tide in the Colne estuary region.*

2.7 *Site Locations for Model Validation*

3 sites were selected for the validation of sea level and 3 sites for current speed and direction, as shown in Fig.13.

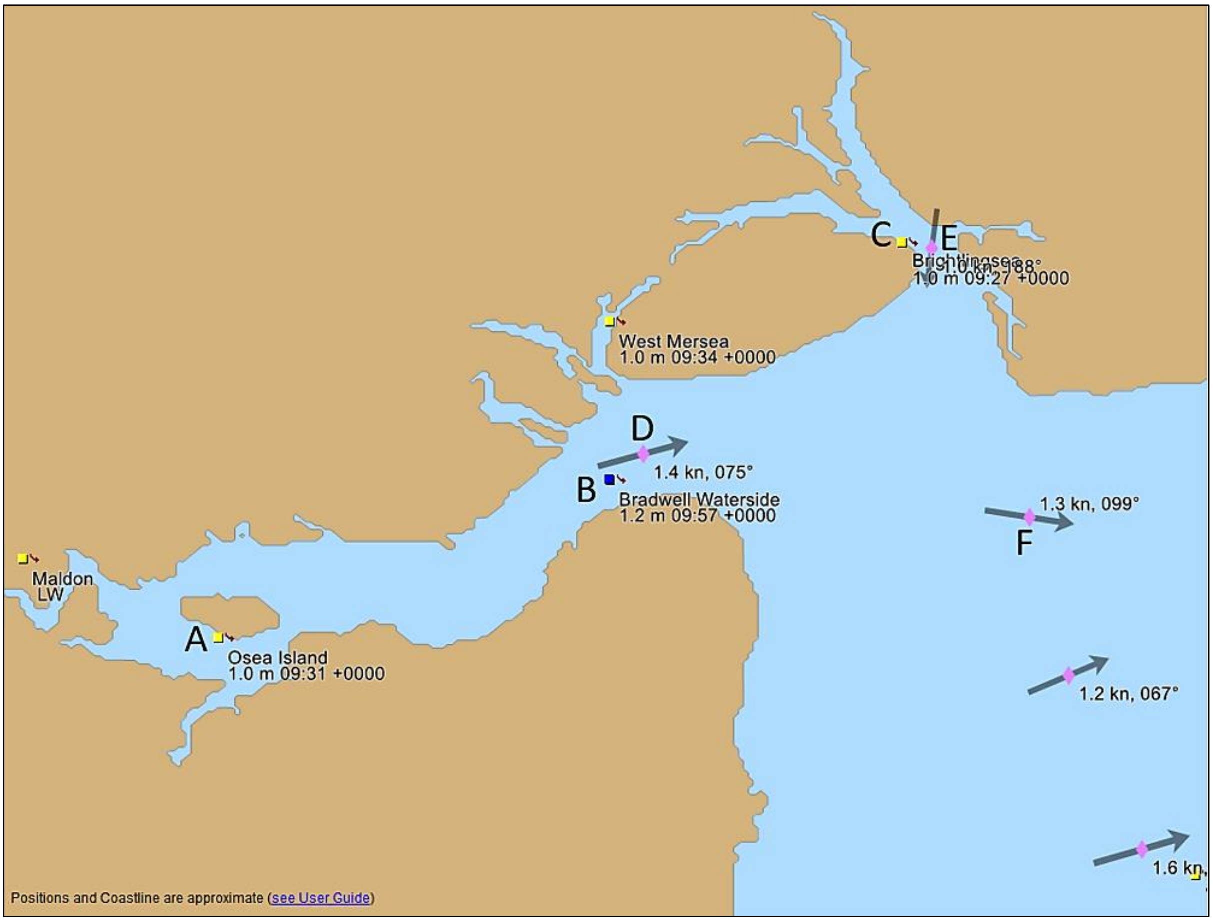

Figure 13 *Site locations for the validation of the hydrodynamic model. A, B and C for sea level and D, E and F for current speed and direction.*

At each of these locations, comparisons were made between model predictions and data from the Admiralty Total Tide (ATT) package [ATT, 2024] for current speed, direction and water level. The ATT software is based on data from Admiralty charts and tidal stream atlases and determines tidal currents, including current velocities, using a combination of empirical tidal harmonic constants and mathematical modelling.

3 Methodology and Results

Model performance was assessed using three metrics: the mean absolute error (MAE), the root mean-square error (RMSE) and the model skill (d2). The first two are standard measures of model accuracy; the third, d2, is taken from [WILLMOTT, 1985] and lies in the range $0 \leq d2 \leq 1$, with d2 = 0 implying zero model skill and d2 = 1.0 indicating perfect skill.

Modelled data were also compared to the SEPA calibration/validation requirements for hydrodynamic and discharge modelling [SEPA, 2019]. Python scripts have been written specifically to allow the direct comparison of ATT and modelled data [CLAWS, 2024].

3.1 *Site A – Osea Island – Sea Surface Height (SSH)*

At the *Site A* measurement location at Osea Island the sea surface height was satisfactorily modelled, with a model skill score of 0.97 (Figure 14 and Table 1). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.38 m and 0.43 m, respectively, are about 8.6% and 9.7% of the spring tide range, respectively. Table 2 shows the comparison of modelled sea surface height compared with the SEPA acceptable range [SEPA, 2019]. In general, the Telemac model data are in satisfactory agreement with the SEPA standards. The plot shown in Figure 14 demonstrates that the sea surface height predictions broadly follow the ATT data.

Table 1. *Model performance statistics for sea surface height (SSH) at the measurement location Site A, Osea Island, between 5th -19th May 2023.*

	SSH
Skill, d2	0.97
Mean Absolute Error (MAE)	0.38 m
Root-Mean-Square Error (RMSE)	0.43 m

Table 2. *Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) at the measurement location Site A, Osea Island, between 5th -19th May 2023.*

	SEPA Standard	**Telemac3D**	**Result**
SSH	+/- 10 % of Spring range (m)	9.7 %	✓
SSH	+/- 15 % of Neap range (m)	13.8 %	✓
Timing of high water / phase	+/- 15 mins	14 mins	✓

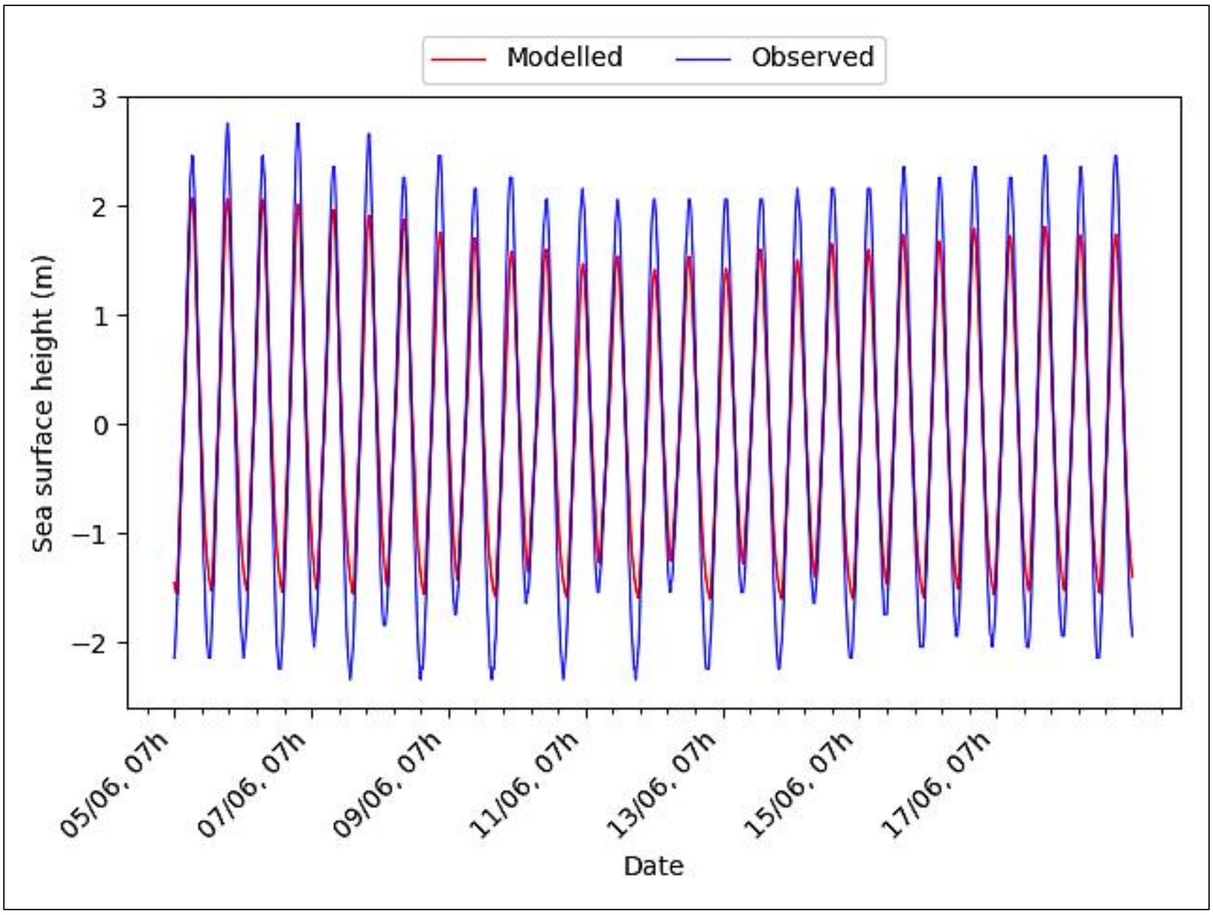

Figure 14 *Comparison between observed and modelled sea surface height at the measurement location Site A, Osea Island, between 5th -19th May 2023. Model skill d2 = 0.97.*

3.2 *Site B – Bradwell Waterside – Sea Surface Height (SSH)*

At the *Site B* measurement location at Bradwell Waterside the sea surface height was satisfactorily modelled, with a model skill score of 0.99 (Figure 15 and Table 3). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.2 m and 0.25 m, respectively, are about 4.5% and 5.6% of the spring tide range, respectively. Table 4 shows the comparison of modelled sea surface height compared with the SEPA acceptable range [SEPA, 2019]. In general, the Telemac model data are in satisfactory agreement with the SEPA standards. The plot shown in Figure 15 demonstrates that the sea surface height predictions were broadly in agreement with the ATT data.

Table 3. *Model performance statistics for sea surface height (SSH) at the measurement location Site B, Bradwell Waterside, between 5th -19th May 2023.*

	SSH
Skill, d2	0.99
Mean Absolute Error (MAE)	0.2 m
Root-Mean-Square Error (RMSE)	0.25 m

Table 4. *Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) at the measurement location Site B, Bradwell Waterside, between 5th -19th May 2023.*

	SEPA Standard	**Telemac3D**	**Result**
SSH	+/- 10 % of Spring range (m)	5.6 %	✓
SSH	+/- 15 % of Neap range (m)	7.9 %	✓
Timing of high water / phase	+/- 15 mins	13 mins	✓

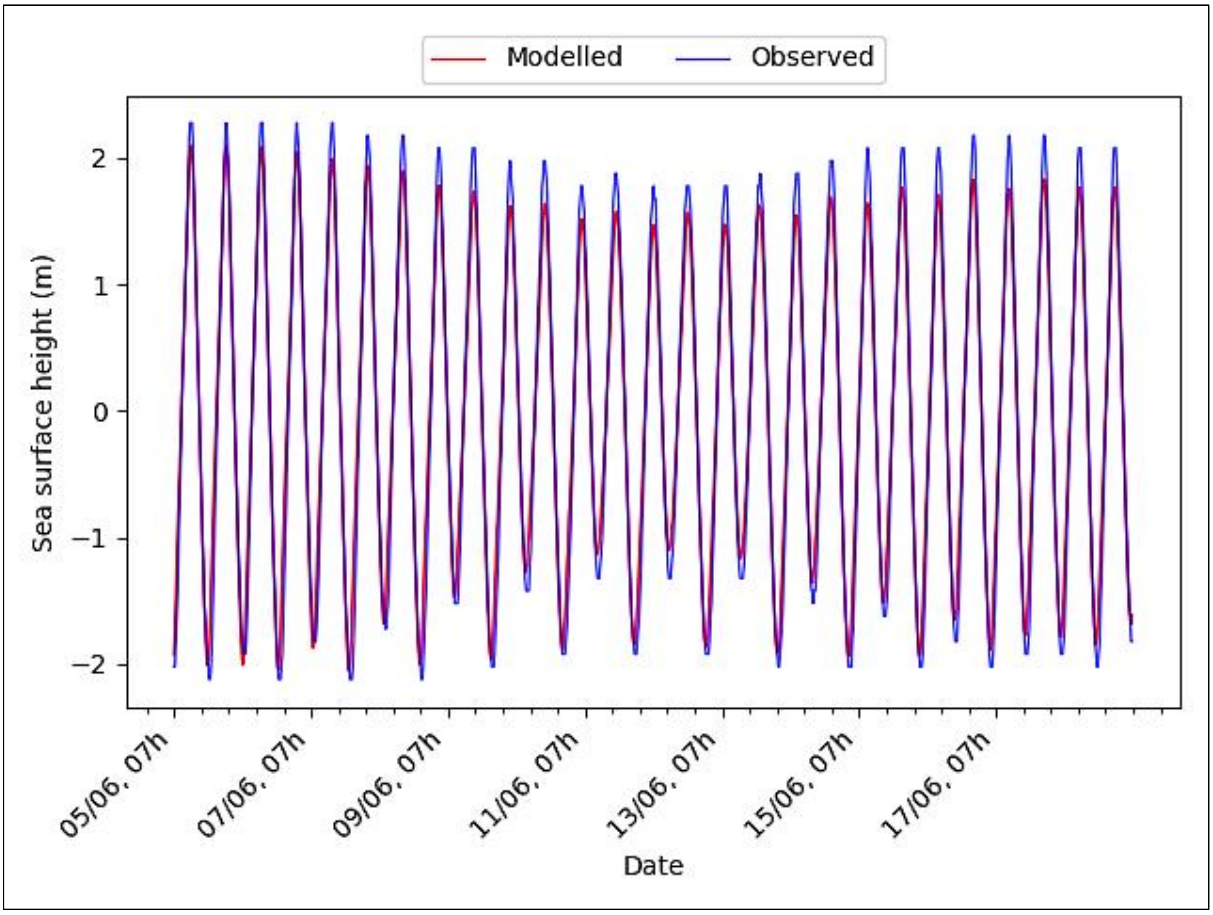

Figure 15 *Comparison between observed and modelled sea surface height at the measurement location Site B, Bradwell Waterside, between 5th -19th May 2023. Model skill d2 = 0.99.*

3.3 *Site C – Brightlingsea – Sea Surface Height (SSH)*

At the *Site C* measurement location at Brightlingsea the sea surface height was satisfactorily modelled, with a model skill score of 0.98 (Figure 16 and Table 5). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.27 m and 0.32 m, respectively, are about 6.1% and 7.2% of the spring tide range, respectively. Table 6 shows the comparison of modelled sea surface height compared with the SEPA acceptable range [SEPA, 2019]. In general, the Telemac model data are in satisfactory agreement with the SEPA standards. The plot shown in Figure 16 demonstrates that the sea surface height predictions were broadly in agreement with the ATT data.

Table 5. *Model performance statistics for sea surface height (SSH) at the measurement location Site C, Brightlingsea, between 5th -19th May 2023.*

	SSH
Skill, d2	0.98
Mean Absolute Error (MAE)	0.27 m
Root-Mean-Square Error (RMSE)	0.32 m

Table 6. *Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) at the measurement location Site C, Brightlingsea, between 5th -19th May 2023.*

	SEPA Standard	**Telemac3D**	**Result**
SSH	+/- 10 % of Spring range (m)	7.2 %	✓
SSH	+/- 15 % of Neap range (m)	10.3 %	✓
Timing of high water / phase	+/- 15 mins	15 mins	✓

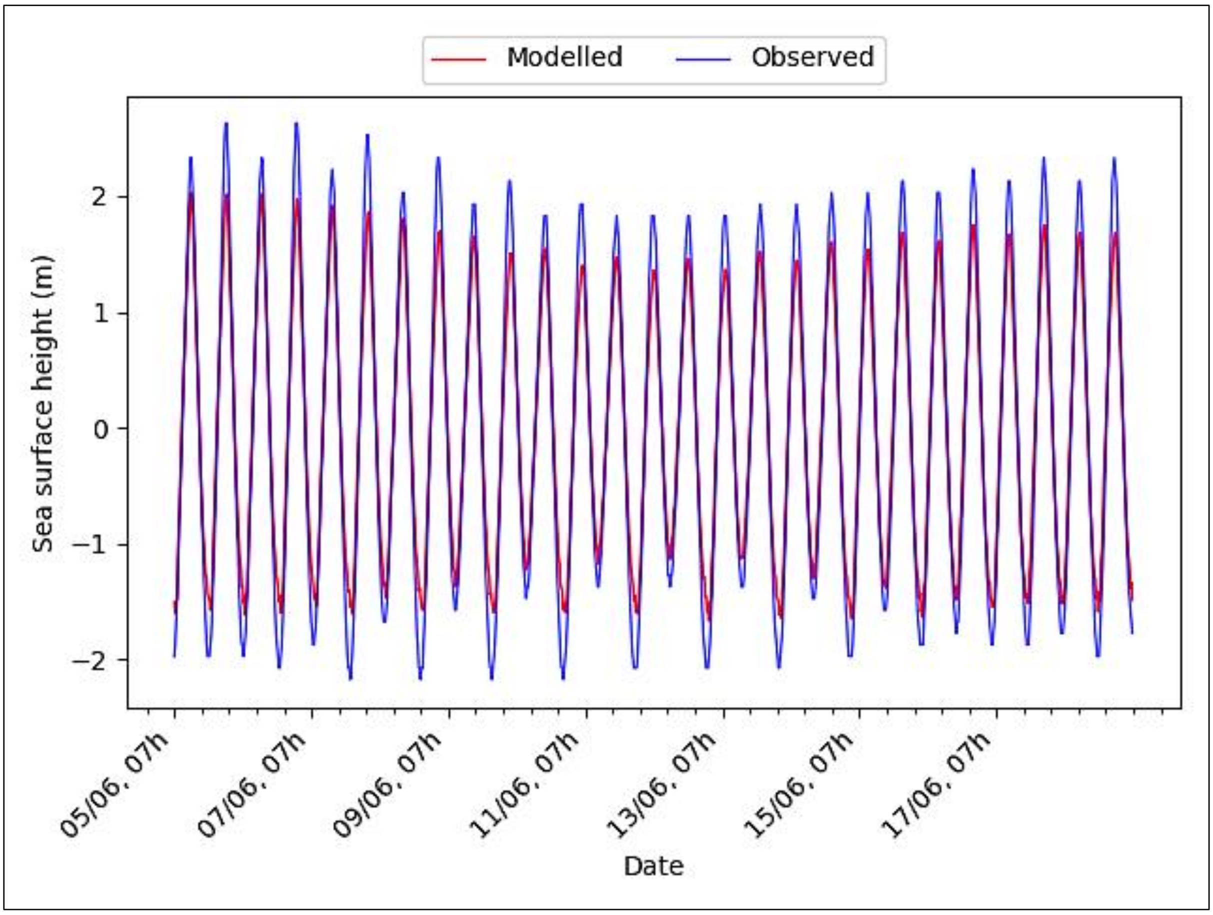

Figure 16 *Comparison between observed and modelled sea surface height at the measurement location Site C, Brightlingsea, between 5th -19th May 2023. Model skill d2 = 0.98.*

3.4 *Site D – Bradwell Waterside – Current Speed and Direction*

At the *Site D* measurement location at Bradwell Waterside the north and east components of velocity at the measurement location were reasonably well reproduced by the model, with values of the model skill, d2, of 0.8 and 0.98, respectively. The values of the MAE and RMSE being in the range 6 – 11 cm s^{-1} (Table 7). The scatter plots and histograms shown in Figures 17-20 demonstrate that the predicted currents were broadly of the same speed and direction as the ATT data.

Table 7. *Model performance statistics for the East and North velocity at the measurement location Site D, Bradwell Waterside, between 5th -19th May 2023.*

	East	North
Skill, d2	0.98	0.8
Mean Absolute Error (MAE)	0.09 m/s	0.06 m/s
Root-Mean-Square Error (RMSE)	0.11 m/s	0.07 m/s

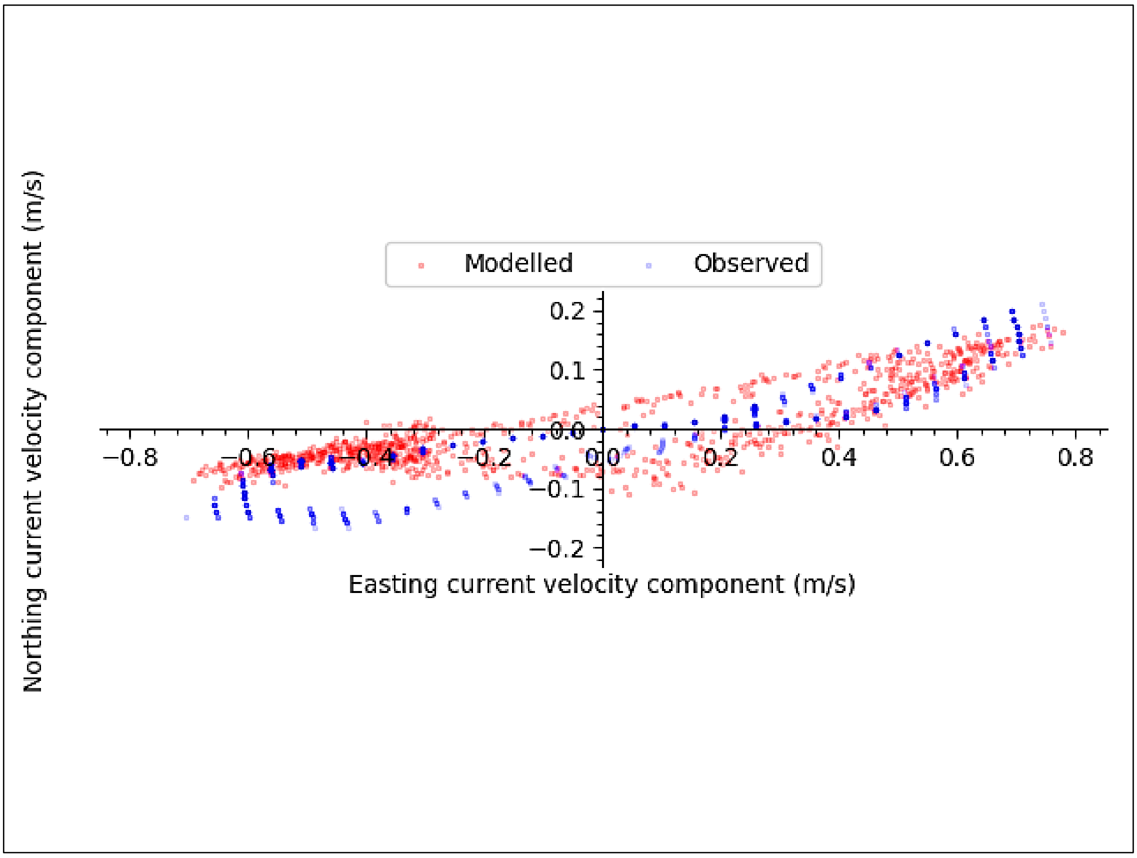

Figure 17 *Scatter plot of observed and modelled velocity at the measurement location Site D, Bradwell Waterside, between 5th -19th May 2023.*

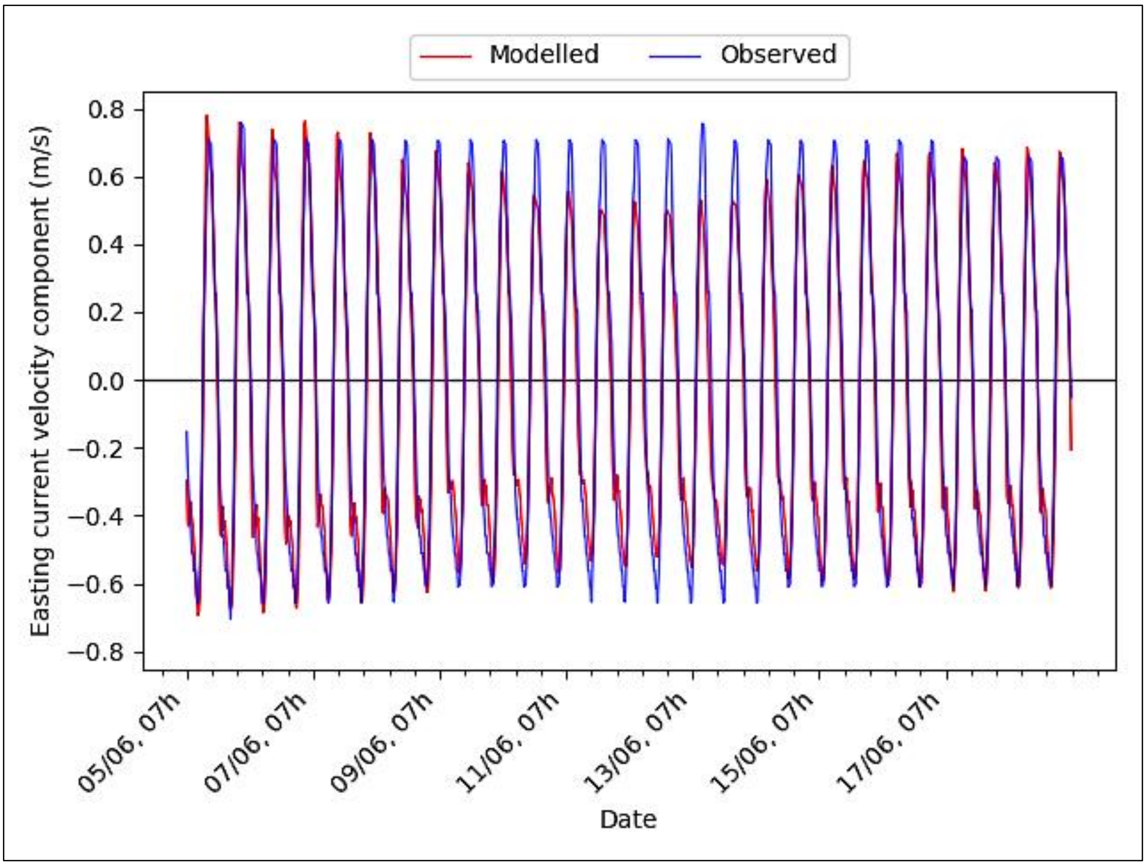

Figure 18 *Comparison between observed and modelled Easting velocity at the measurement location Site D, Bradwell Waterside, between 5th -19th May 2023. Model skill d2 = 0.98.*

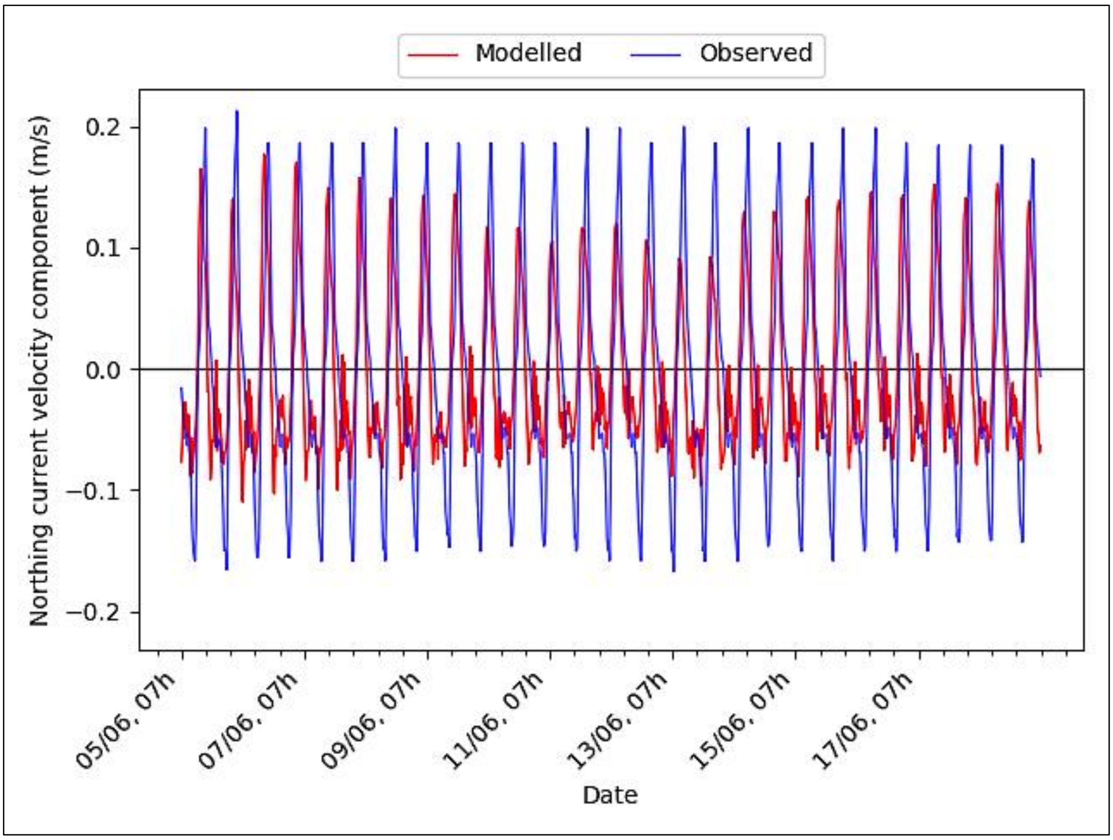

Figure 19 *Comparison between observed and modelled Northing velocity at the measurement location Site D, Bradwell Waterside, between 5th -19th May 2023. Model skill d2 = 0.8.*

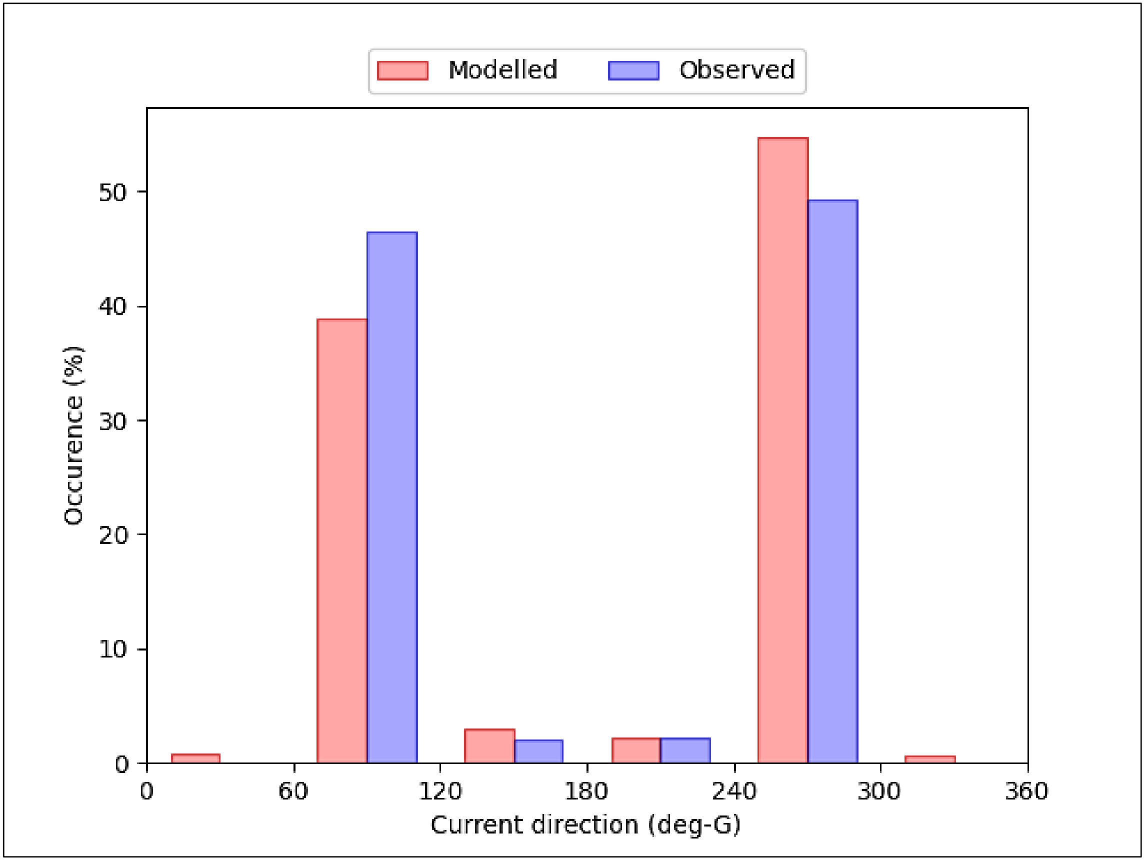

Figure 20 *Histogram of observed and modelled current direction at the measurement location Site D, Bradwell Waterside, between 5th -19th May 2023. Model skill d2 = 0.99.*

3.5 *Site E – Brightlingsea – Current Speed and Direction*

At the *Site E* measurement location at Brightlingsea the north and east components of velocity at the measurement location were less well reproduced by the model in comparison with sites D and F, with values of the model skill, d2, of 0.65 and 0.33, respectively. The values of the MAE and RMSE being in the range 7 – 31 cm s^{-1} (Table 8). The scatter plots and histograms shown in Figures 21-24 show the predicted current speed and direction in comparison with the ATT data.

Table 8. *Model performance statistics for the East and North velocity at the measurement location Site E, Brightlingsea, between 5th -19th May 2023.*

	East	**North**
Skill, d2	0.33	0.65
Mean Absolute Error (MAE)	0.07 m/s	0.26 m/s
Root-Mean-Square Error (RMSE)	0.09 m/s	0.31 m/s

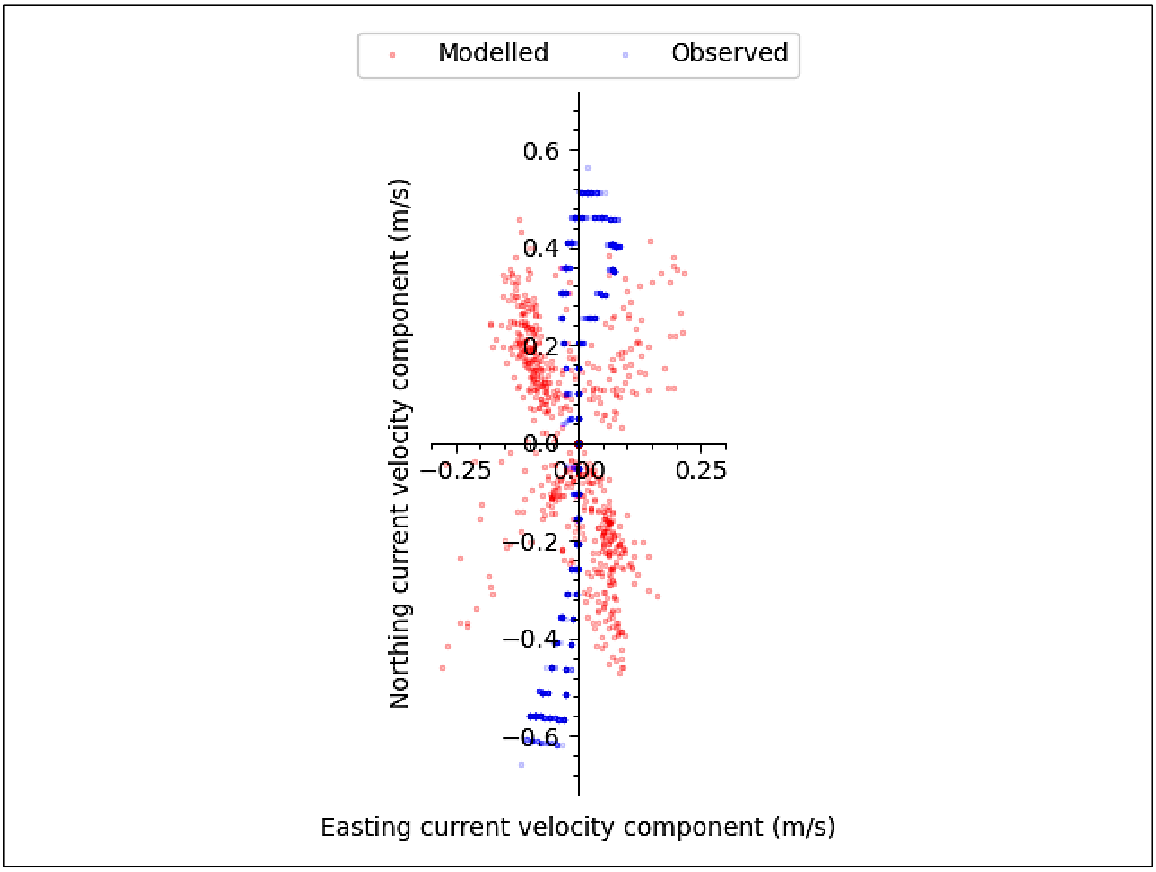

Figure 21 *Scatter plot of observed and modelled velocity at the measurement location Site E, Brightlingsea, between 5th -19th May 2023.*

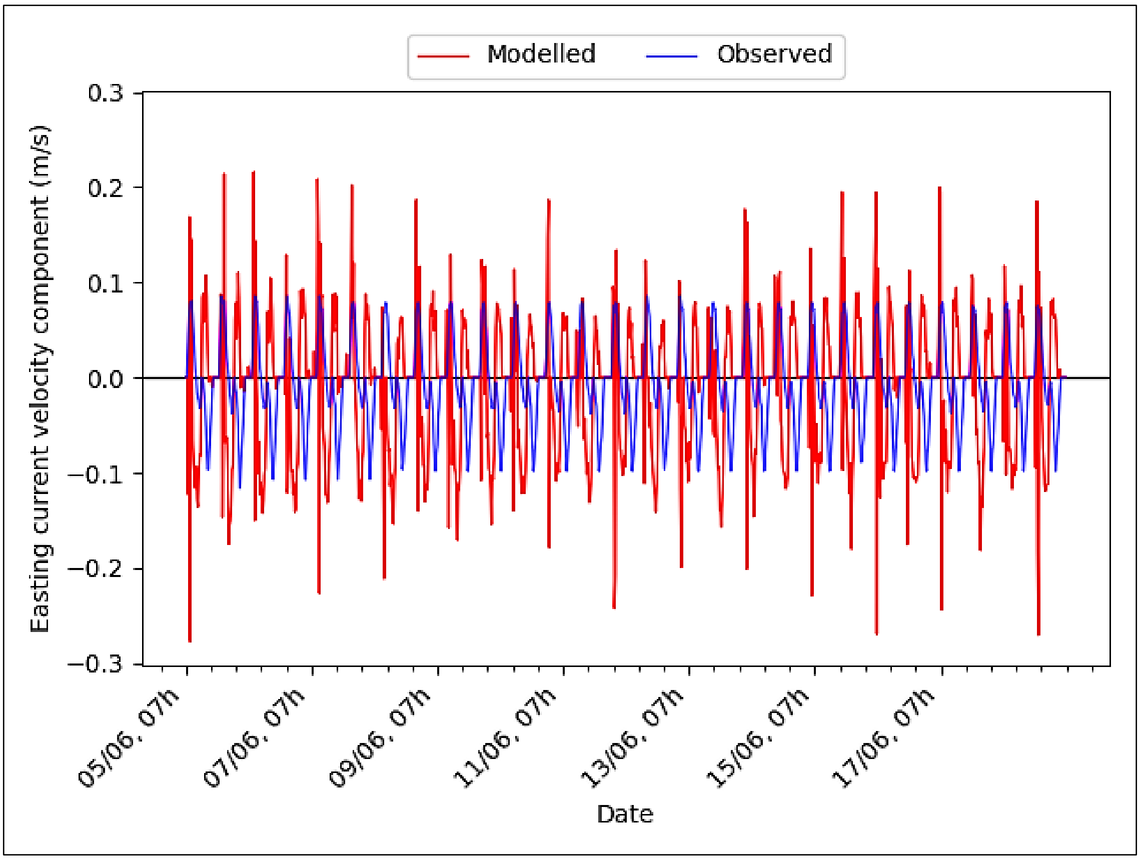

Figure 22 *Comparison between observed and modelled Easting velocity at the measurement location Site E, Brightlingsea, between 5th -19th May 2023. Model skill d2 = 0.33.*

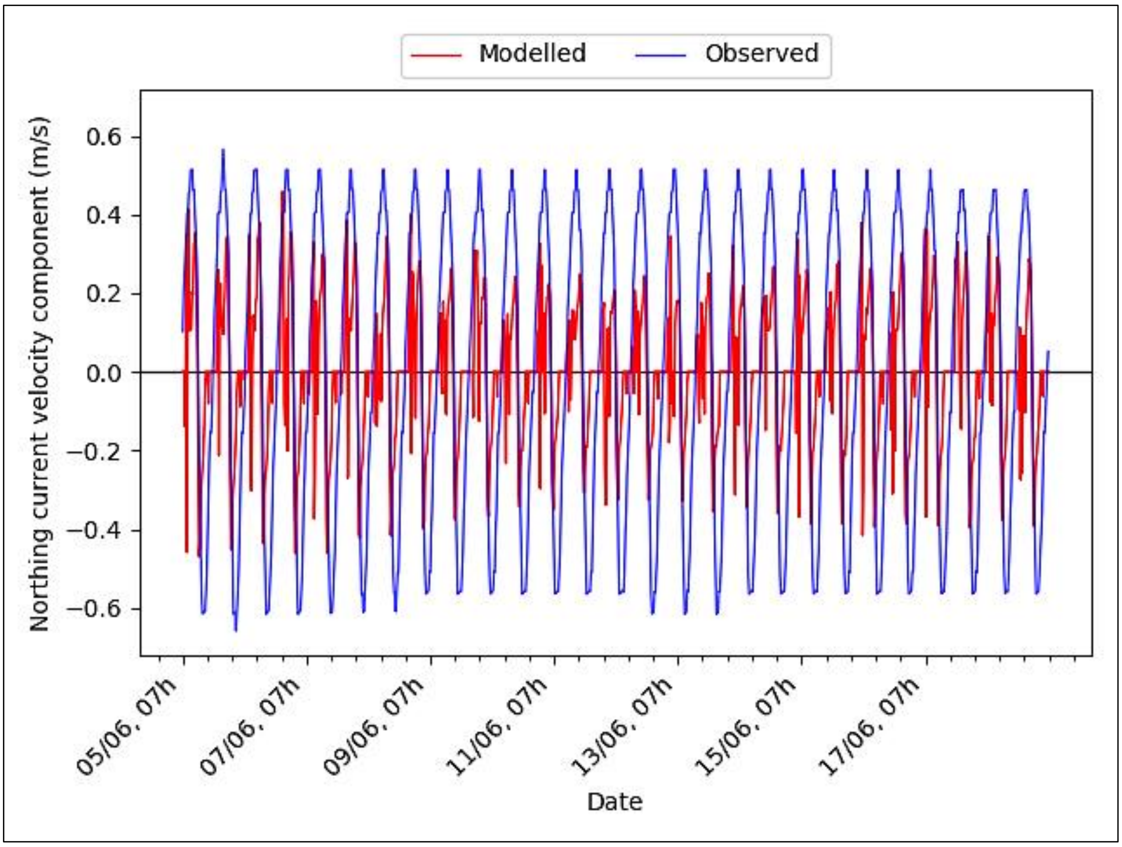

Figure 23 *Comparison between observed and modelled Northing velocity at the measurement location Site E, Brightlingsea, between 5th -19th May 2023. Model skill d2 = 0.65.*

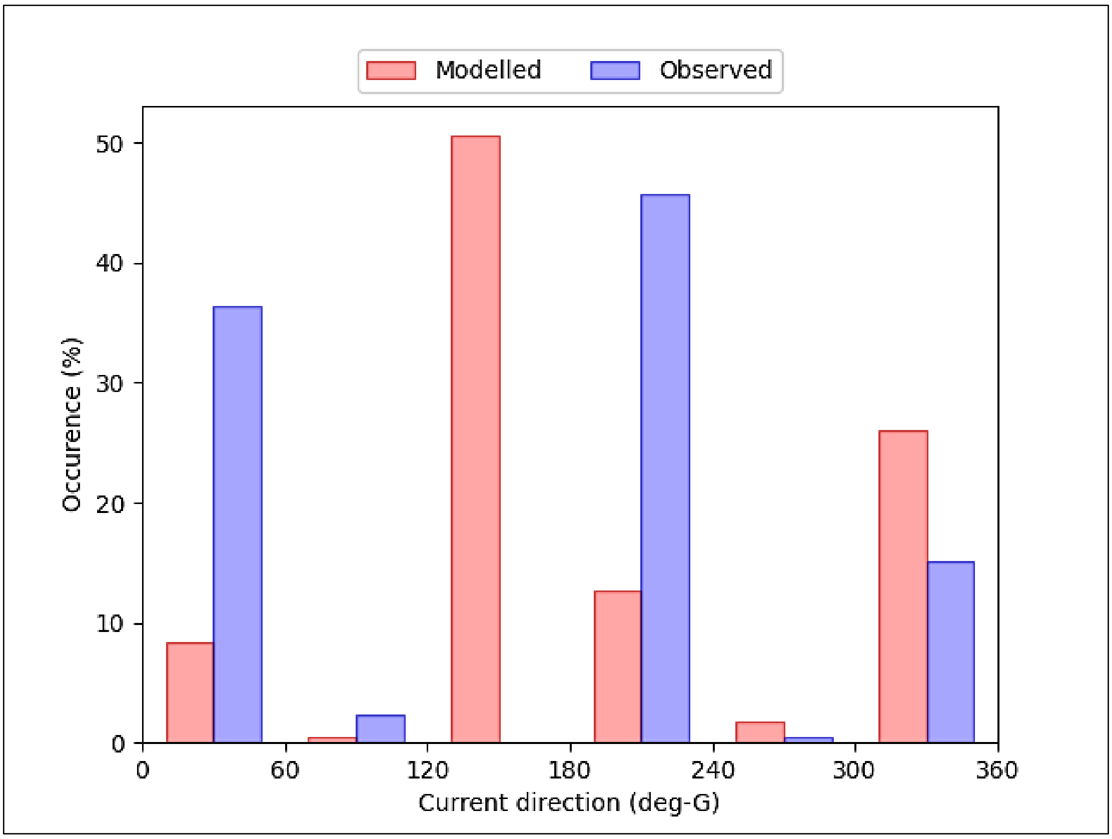

Figure 24 *Histogram of observed and modelled current direction at the measurement location Site E, Brightlingsea, between 5th -19th May 2023. Model skill d2 = 0.29.*

3.6 *Site F – Current Speed and Direction*

At the *Site F* measurement location the north and east components of velocity at the measurement location were satisfactorily reproduced by the model in comparison with values of the model skill, d2, of 0.8 and 0.98, respectively. The values of the MAE and RMSE being in the range 9 – 16 cm s^{-1} (Table 9). The scatter plots and histograms shown in Figures 25-28 show the predicted current speed and direction in comparison with the ATT data.

Table 9. *Model performance statistics for the East and North velocity at the measurement location Site F between 5th -19th May 2023.*

	East	**North**
Skill, d2	0.98	0.8
Mean Absolute Error (MAE)	0.13 m/s	0.09 m/s
Root-Mean-Square Error (RMSE)	0.16 m/s	0.11 m/s

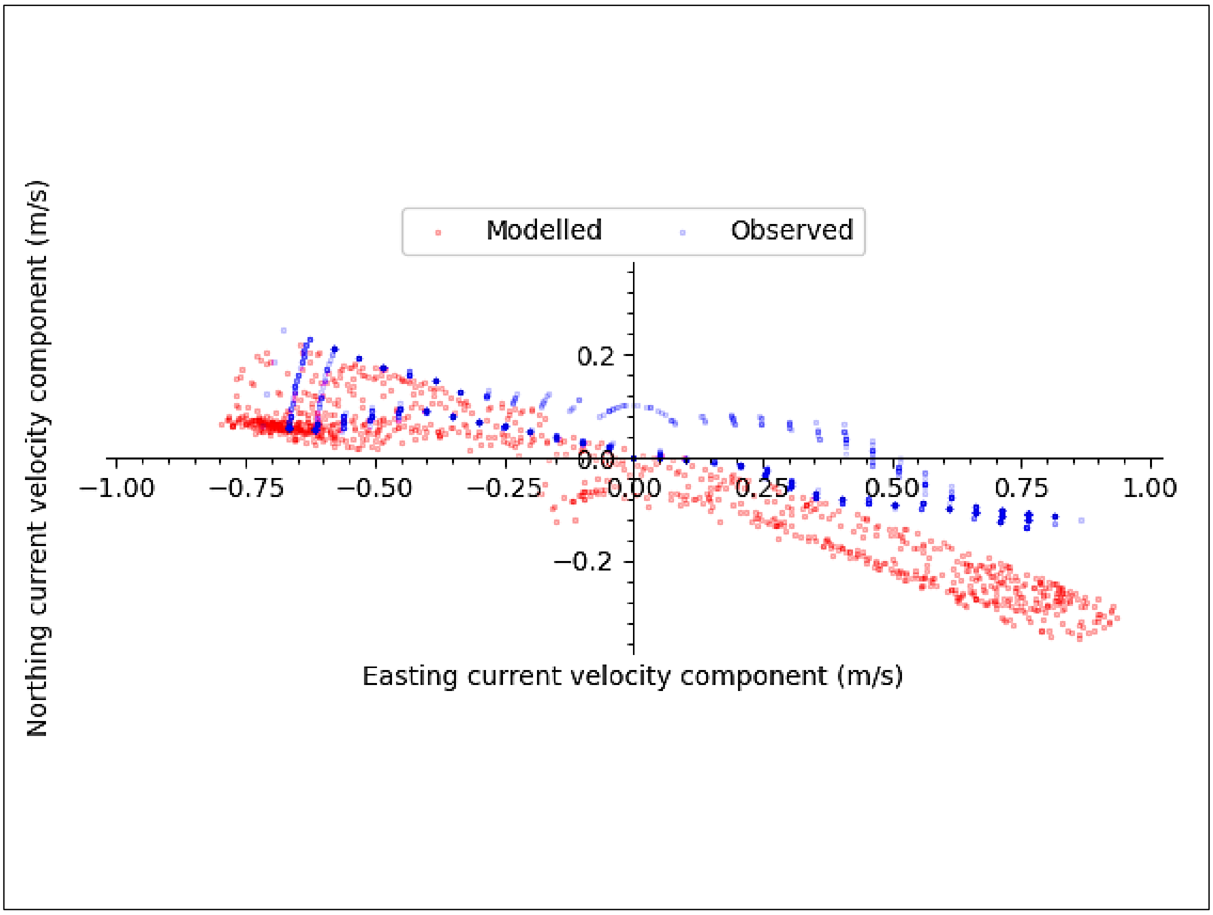

Figure 25 *Scatter plot of observed and modelled velocity at the measurement location Site F between 5th -19th May 2023.*

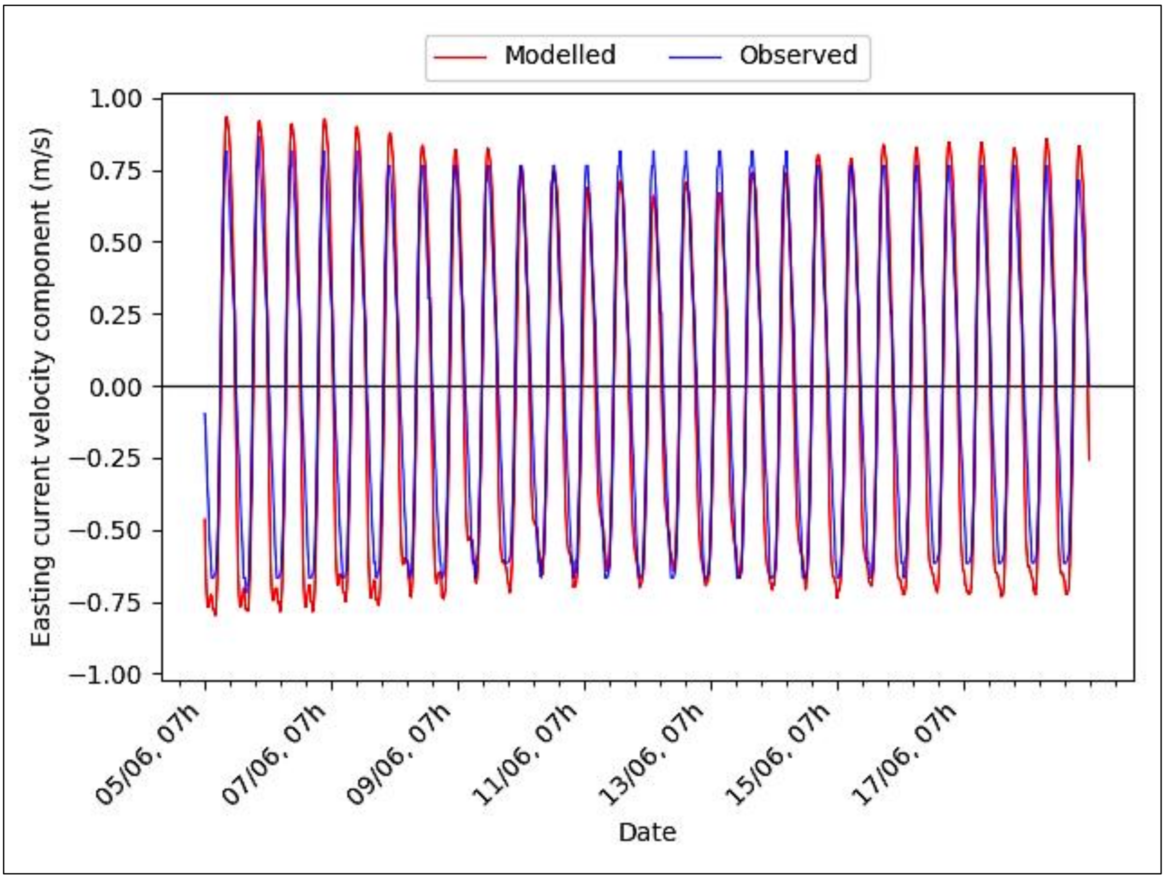

Figure 26 *Comparison between observed and modelled Easting velocity at the measurement location Site F between 5th -19th May 2023. Model skill d2 = 0.98.*

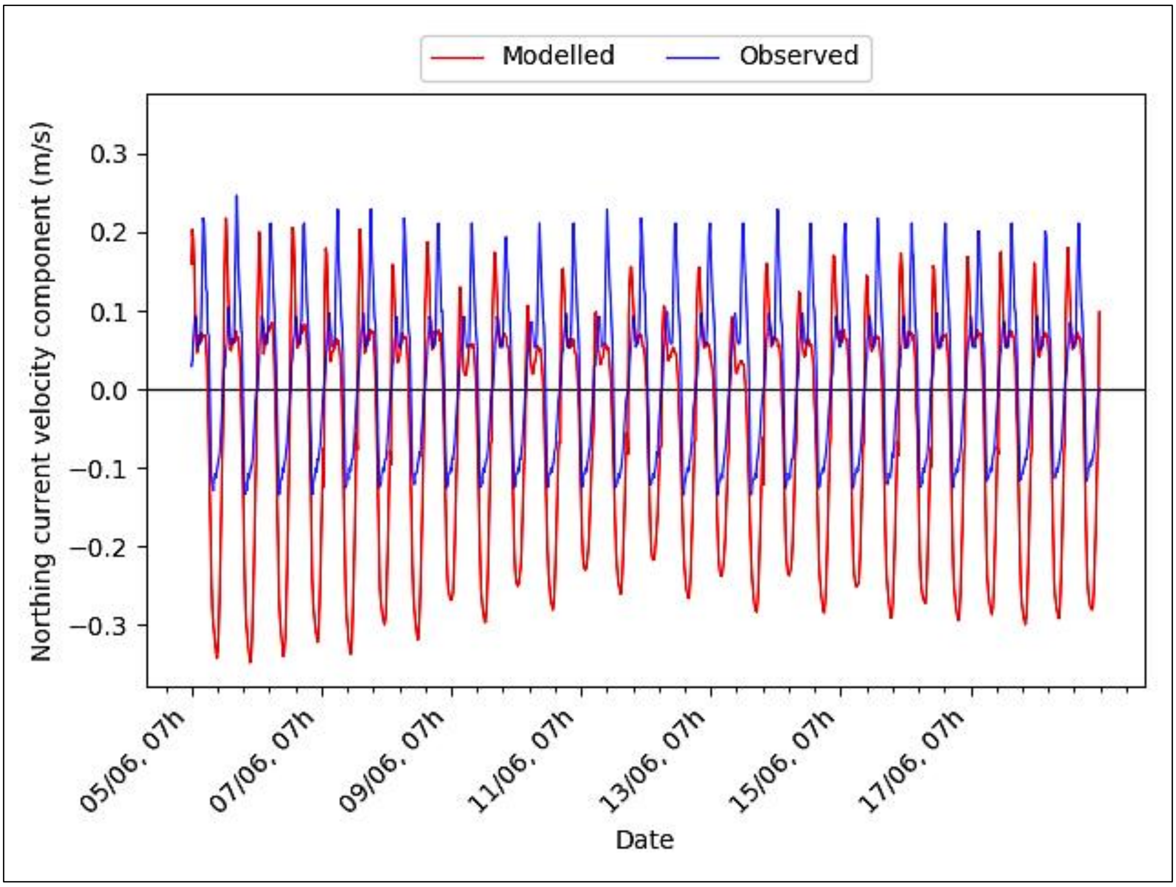

Figure 27 *Comparison between observed and modelled Northing velocity at the measurement location Site F between 5th -19th May 2023. Model skill d2 = 0.8.*

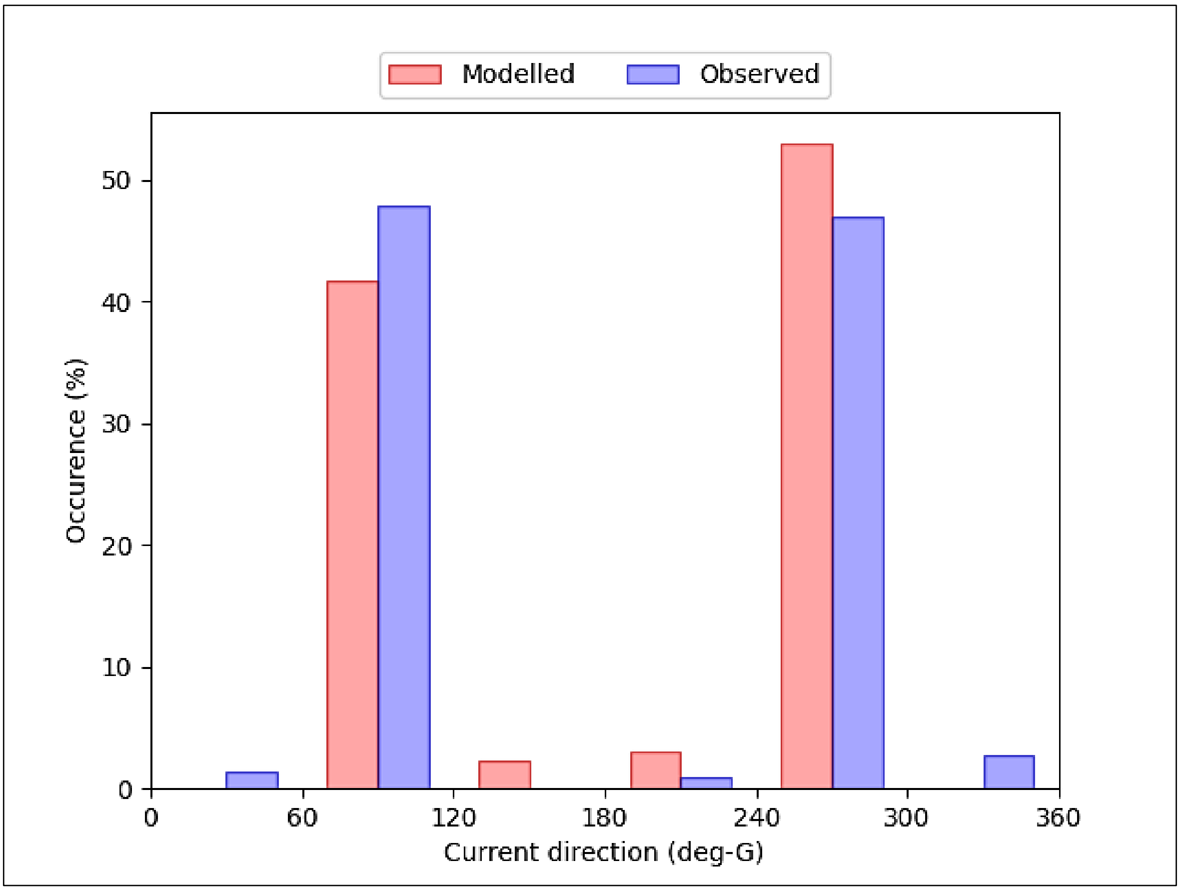

Figure 28 *Histogram of observed and modelled current direction at the measurement location Site F between 5th -19th May 2023. Model skill d2 = 0.99.*

3.9 *Comparisons Against Previous Studies*

Previous modelling studies of the hydrodynamics in the Firth of Forth have been undertaken as part of the design of the Queensferry Crossing [FRC, 2009]. In this study, the commercial hydrodynamics modelling code MIKE3 was employed. An average RMS error for current speed magnitude of 0.14 m/s was found in the MIKE3 study compared with a value of 0.18 m/s for the Telemac study in this document. Both of these values fall within the “+/- 0.2 m/s” FWR guideline [FWR, 1993].

For the predicted water level, the average RMS error in the MIKE3 Queensferry study was 0.21 m compared with the Telemac value of 0.3 m presented here. Both of these values lie within the “+/- 0.1 m at the mouth, +/- 0.3 m at the head” FWR guideline [FWR, 1993].

4. Conclusions

A three-dimensional hydrodynamic (HD) model of the Blackwater and Colne estuaries has been constructed using the Telemac code [TELEMAC, 2024]. The 3D model extends from Walton-on-the-Naze in the north-east to Shoeburyness in the south-west and spans the waters of the Blackwater, Crouch, Roach and Colne estuaries Marine Conservation Zone (MCZ).

The model correctly simulates tide propagation over the MCZ region, and its 3D approach reasonably describes flow currents in terms of magnitude and direction. Model predictions generally satisfy specific calibration/validation requirements for hydrodynamic and discharge modelling [FWR, 1993] [SEPA, 2019] and compare favourably with similar previous work [FRC, 2009].

The Telemac model provides general insight into spatial and temporal variations in the flow environment in the waters of the Blackwater, Crouch, Roach and Colne estuaries Marine Conservation Zone (MCZ). It offers a suitable basis for assessing near-field and far-field dispersion effects of particulate biological and inert matter such as oyster larvae, Escherichia coli (E. coli), nutrients and plastic waste.

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