Validation of a Telemac 3D Hydrodynamics Model of the Firth of Clyde

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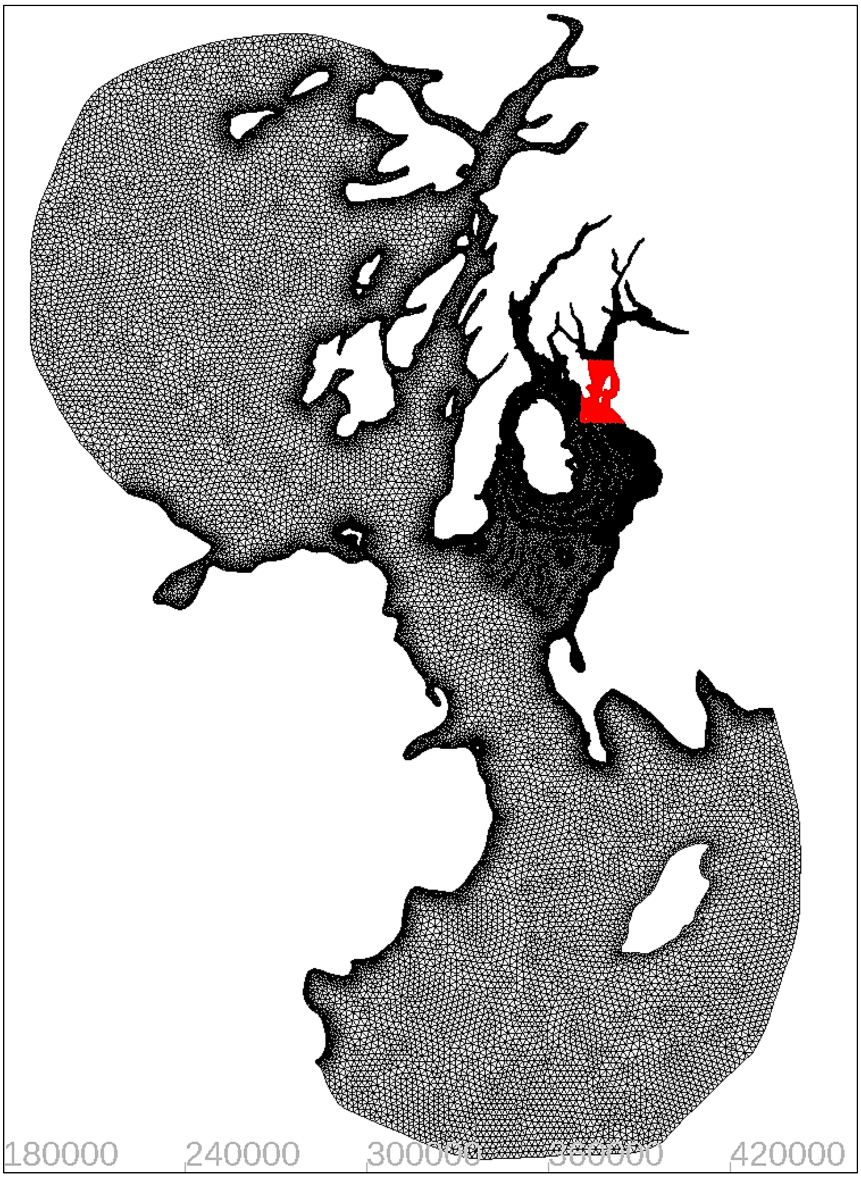

Executive Summary

A three-dimensional hydrodynamic (HD) model of the West Coast of Scotland and Firth of Clyde has been constructed using the Telemac code [TELEMAC, 2023]. The 3D model domain extends from the Irish Sea in the South to the Atlantic Ocean in the North and includes the main islands of the West Coast and Clyde Sea. Initial model validation has been reported elsewhere [SCANLON, 2023] and this report focuses on further validation of the HD model against physical observations in the Firth of Clyde.

The oceanography of the West Coast and Clyde estuary represents an area of complex water circulation exhibiting various levels of density stratification throughout the year. For the 3D model, a non-hydrostatic approach is used. Freshwater sources from local rivers discharging into sea loch areas were included, to model salinity and temperature differences that act as an important driving force for fluid movement in fjordic systems such as those found on the West Coast.

The influence of meteorological wind forcing and heat exchange on the modelled current speeds was included for the time of year of the study. Coriolis force for Earth spin and sea-bed friction were also included in the model.

The model was validated against observed hydrographic data (water levels and currents) with a specific focus on a measurement location at Little Cumbrae.

The model produces a satisfactory simulation of the propagation of the tide in the Firth of Clyde and provides a reasonable description of the flow currents within, in terms of current magnitude and direction. In general, the model data compares favourably against the SEPA calibration/validation requirements for hydrodynamic and discharge modelling [SEPA, 2019]. Python scripts have been written to allow the direct comparison of observed and modelled data as part of the open source platform CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS, 2023]. Other particle-based modules in the CLAWS toolbox include those for bath treatments, dissolved nutrients, solid particle waste and parasitic salmon lice.

With this report and other validation studies [SCANLON, 2023] it is concluded that the Telemac hydrodynamic model can capture satisfactorily the general dynamics of the water levels and current circulation around the West Coast of Scotland and Clyde Estuary.

Such models offer general insight into the spatial and temporal variation in the flow environment around the West Coast of Scotland. Coupled with a suitable biological sea lice model they also provide a suitable basis for modelling sea lice impact on wild salmon and sea trout and an assessment of both the near- and far-field dispersion effects of lice treatment pesticides, solid waste and dissolved nutrients.

About the Report Authors

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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 postdoctoral 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 impact of sea lice, pesticides, nutrients and waste emanating from existing and proposed fish farms on the West Coast of Scotland.

Operational fish farms have the potential to affect the marine environment in several ways, via the release of waste in the form of dissolved nutrients, particulate organic matter, bath treatment pesticides and live parasitic salmon lice.

The report describes the development and validation of a 3D hydrodynamics model to capture adequately the current patterns around Scotland's West coast and islands with a focus on the Firth of Clyde.

A 3D hydrodynamics approach based on the Telemac code [TELEMAC, 2023] has been employed. The hydrodynamic model contains the influence of weather forcing, atmosphere-water heat transfer and stratification brought about by 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 the model data compares against the SEPA calibration/validation requirements for hydrodynamic and discharge modelling [SEPA, 2019]. The Python scripts form part of the open source toolbox CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS, 2023]. Other particle-based modules in the CLAWS software suite include those for pesticide treatments, dissolved nutrients, solid particle waste and salmon lice.

2 Background Information

2.1 *Site location*

The focus of the validation effort is at a measurement location to the West of Little Cumbrae as shown in Figure 1. Data for sea level and water current speed and direction were extracted at this site and values compared with the Telemac model output between the 4th-26th October 2017.

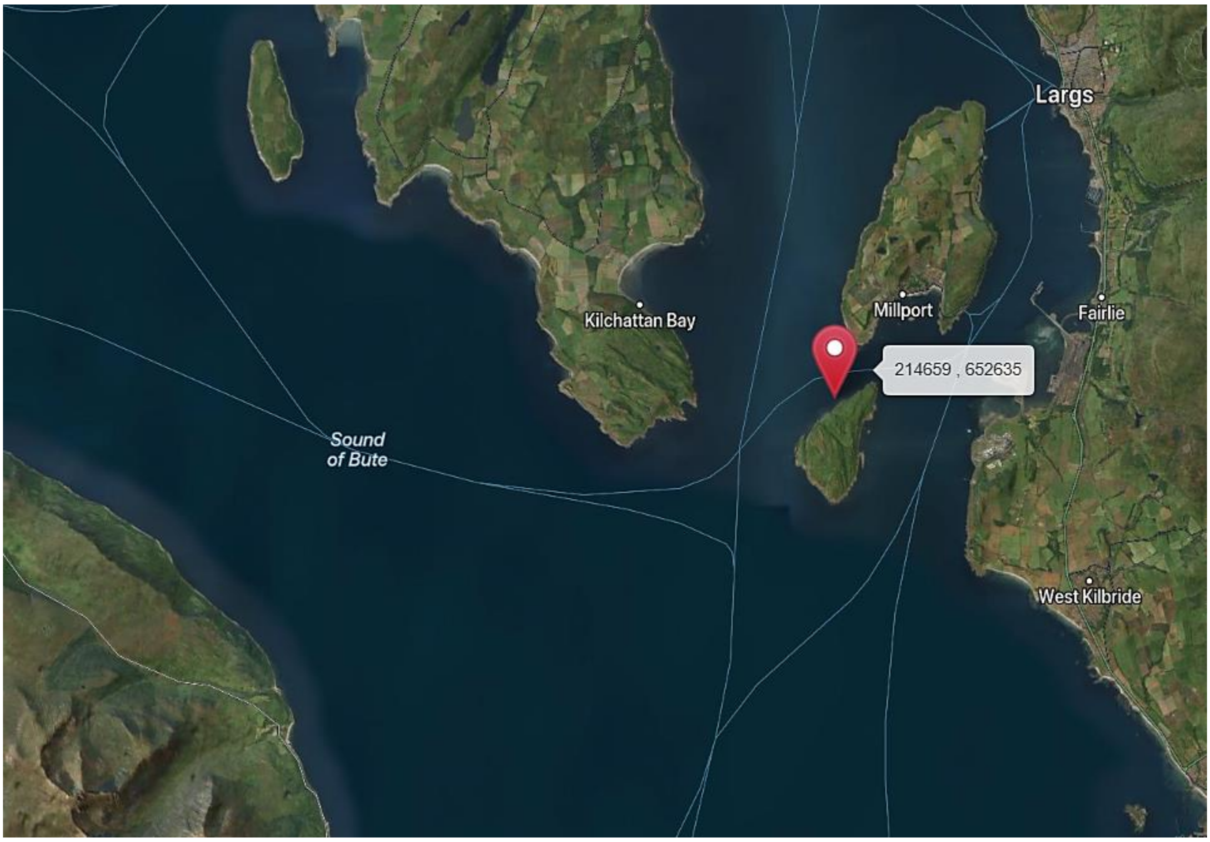

Figure 1 *Location of physical measurement data point to the West of Little Cumbrae.*

2.2 *Hydrodynamic model*

The modelling approach in 3D was to employ the non-hydrostatic version of Telemac3D across the West Coast of Scotland and Firth of Clyde, the extent of which is shown in Figure 2.

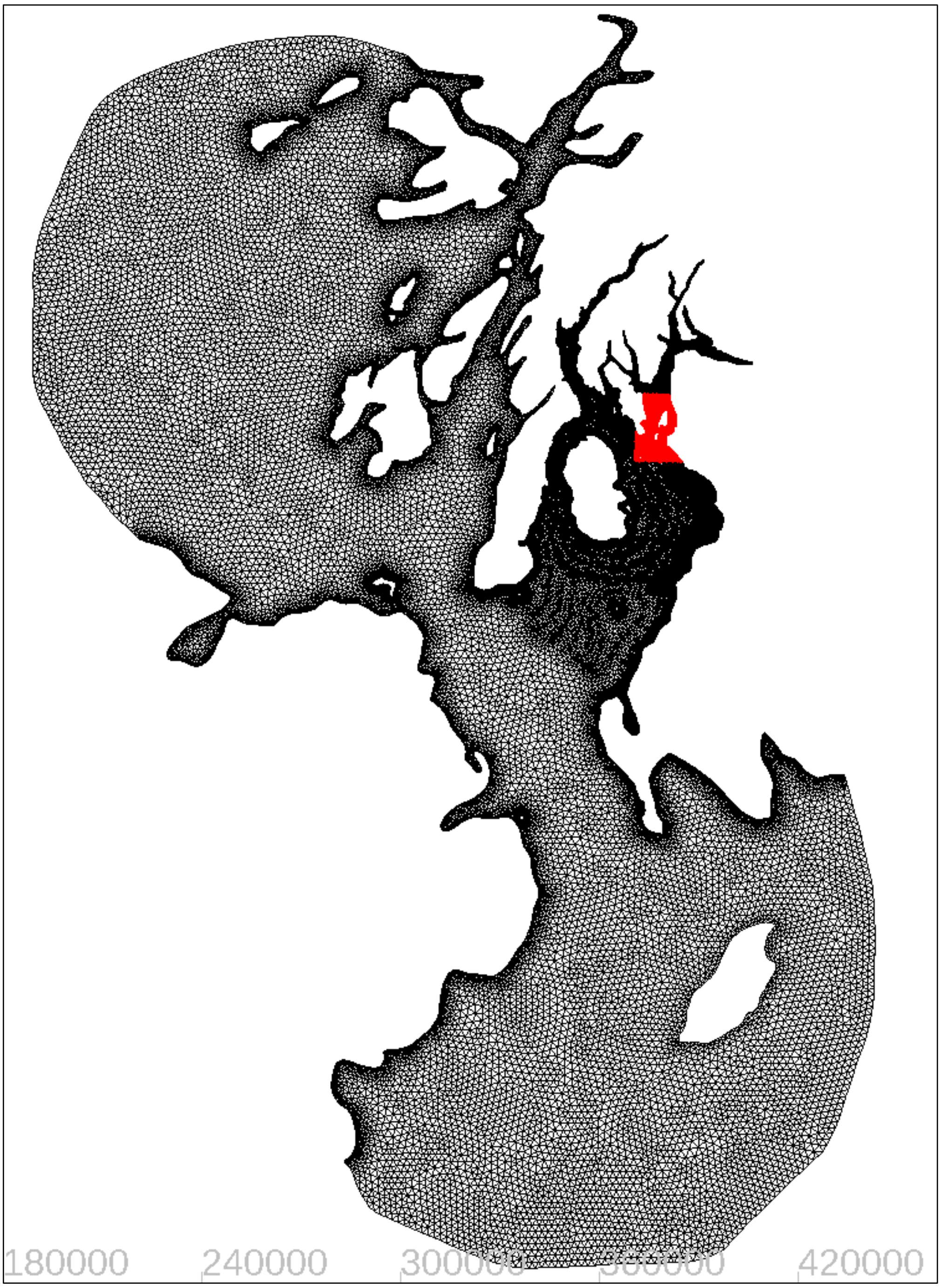

Figure 2 *Computational mesh – red zone represents the area of focus around Little Cumbrae (see Section 2.3).*

In total, the mesh contained 557,150 nodes and 1,026,640 elements with 10 terrain-following vertical sigma layers. A hydrodynamic time-step size of 10 s was employed over the run period from the 4th-26th October 2017 and data was extracted at 20-minute intervals. Note that the dates above refer to the main simulations and that the spin-up simulations to develop the salt and heat fields ran for four days prior to the start date given above.

Extensive model description, validation and verification tests have previously been undertaken against physical data and inter-model comparisons with the Scottish Shelf Model [SSM, 2023] results and these will only be summarised here. For further details see [SCANLON, 2023].

The boundary conditions for the velocities and surface elevations at the offshore open boundaries were obtained from the OSU TPXO European Shelf regional model (11 tidal constituents: M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4) [Egbert, 2002]. Initial values of temperature and salinity were set to 12 ^{o}C and 33.1 PSU, respectively [McIntyre, 2012], and zero gradient boundary conditions applied at the open sea boundaries.

Wind forcing and atmosphere-water heat exchange were included using meteorological data from the ERA5 Copernicus climate data store at 6-hourly intervals [ERA, 2023].

Fresh water inputs were included for 38 rivers across the system with estimates of daily mean river flow for gauged catchments taken from 1960 to 2015 [G2G, 2018]. The principal freshwater flows came from the Clyde, the Leven and the rivers along the Ayrshire coast. Water density was calculated according to the equation of state for density as a function of temperature T (^{o}C) and salinity S (PSU) [SCANLON, 2023].

Finally for turbulence closure the standard k-epsilon model was used in both horizontal and vertical directions [SCANLON, 2023].

2.3 *Reducing the size of the hydrodynamics data set*

The 3D Telemac hydrodynamics model consists of a large data set of flow variables with a file size of 38.2 Gb. It would be beneficial in terms of data handling and manipulation of the hydrodynamic data set could be reduced in size to one focusing on the area around Little Cumbrae. A Python script has been created to achieve this reduction and the file size for the hydrodynamics is reduced substantially from 38.2 Gb to 3.1 Gb.

Figure 3 shows the GeoJSON polygon used to crop the larger model. For further details on the cropping procedure see [CLAWS, 2023].

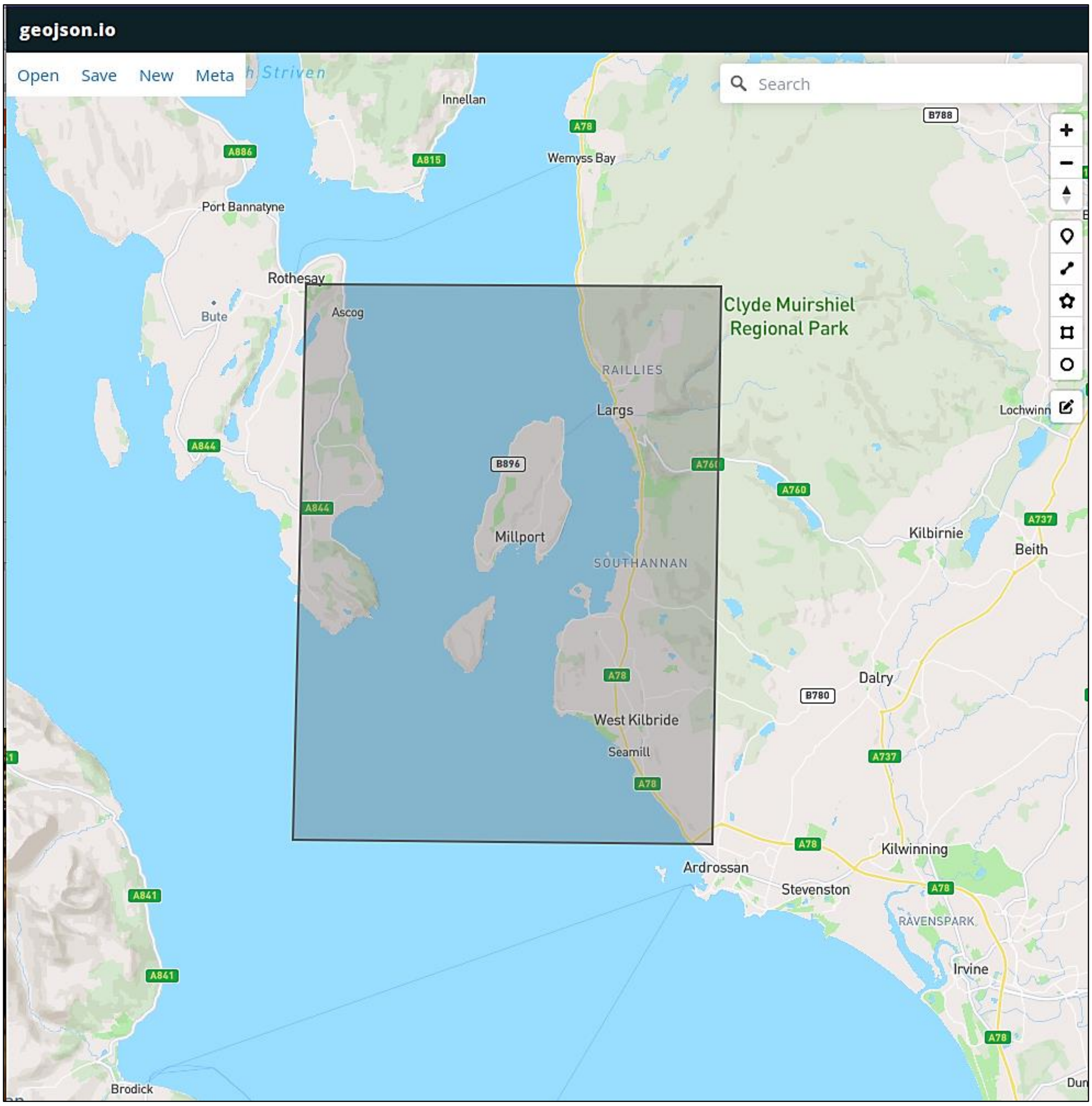

Figure 3 *GeoJSON polygon used to define the zone for hydrodynamic mesh reduction – see [CLAWS, 2023] for further details.*

Figures 4 and 5 show the original model mesh (38.2 Gb, black) and the cropped model (3.1 Gb, red) that is used for the hydrodynamic analysis.

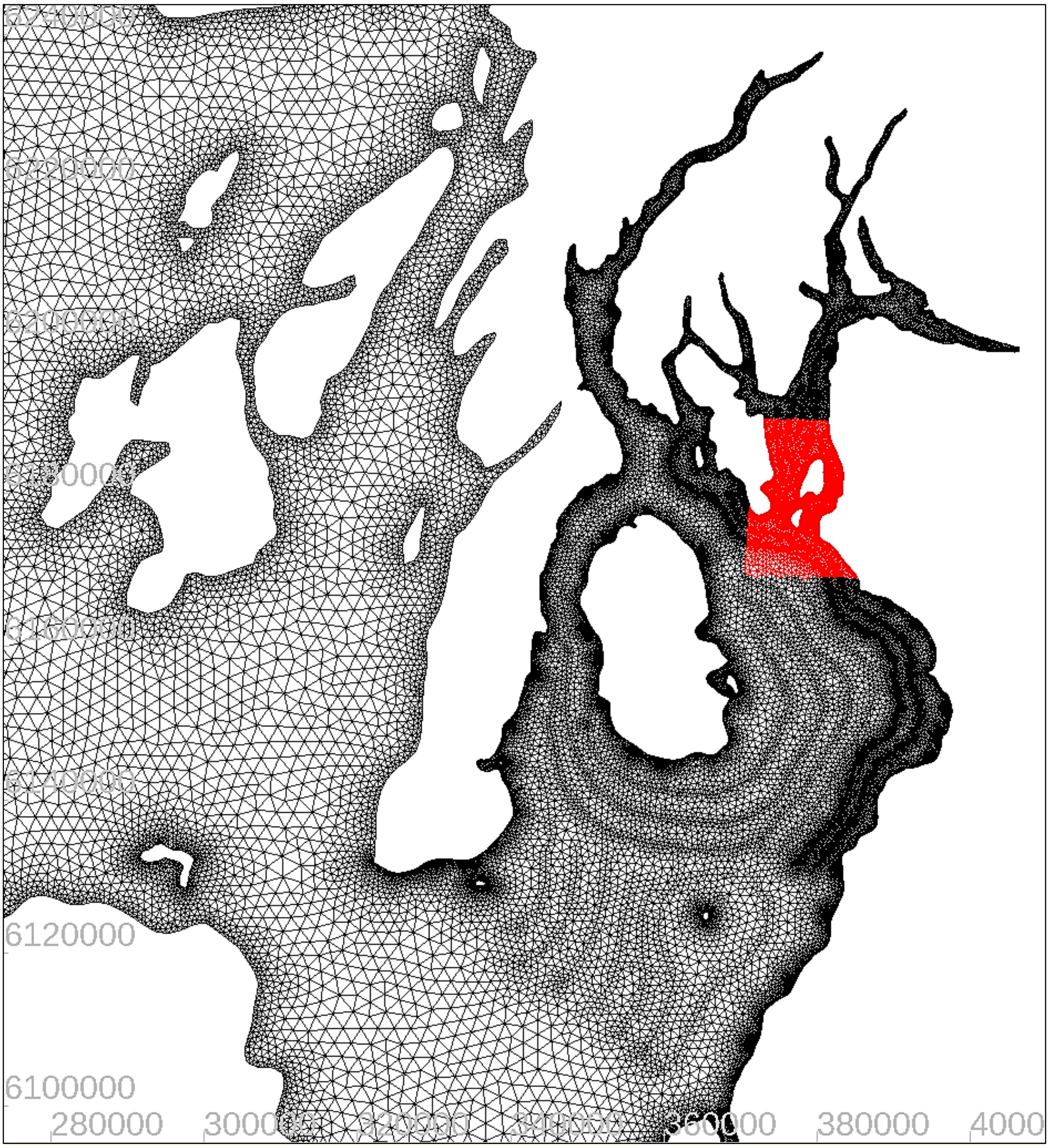

Figure 4 *Zoomed view of the original Telemac 3D hydrodynamics mesh (38.2 Gb, black) and the reduced size model (3.1 Gb, red).*

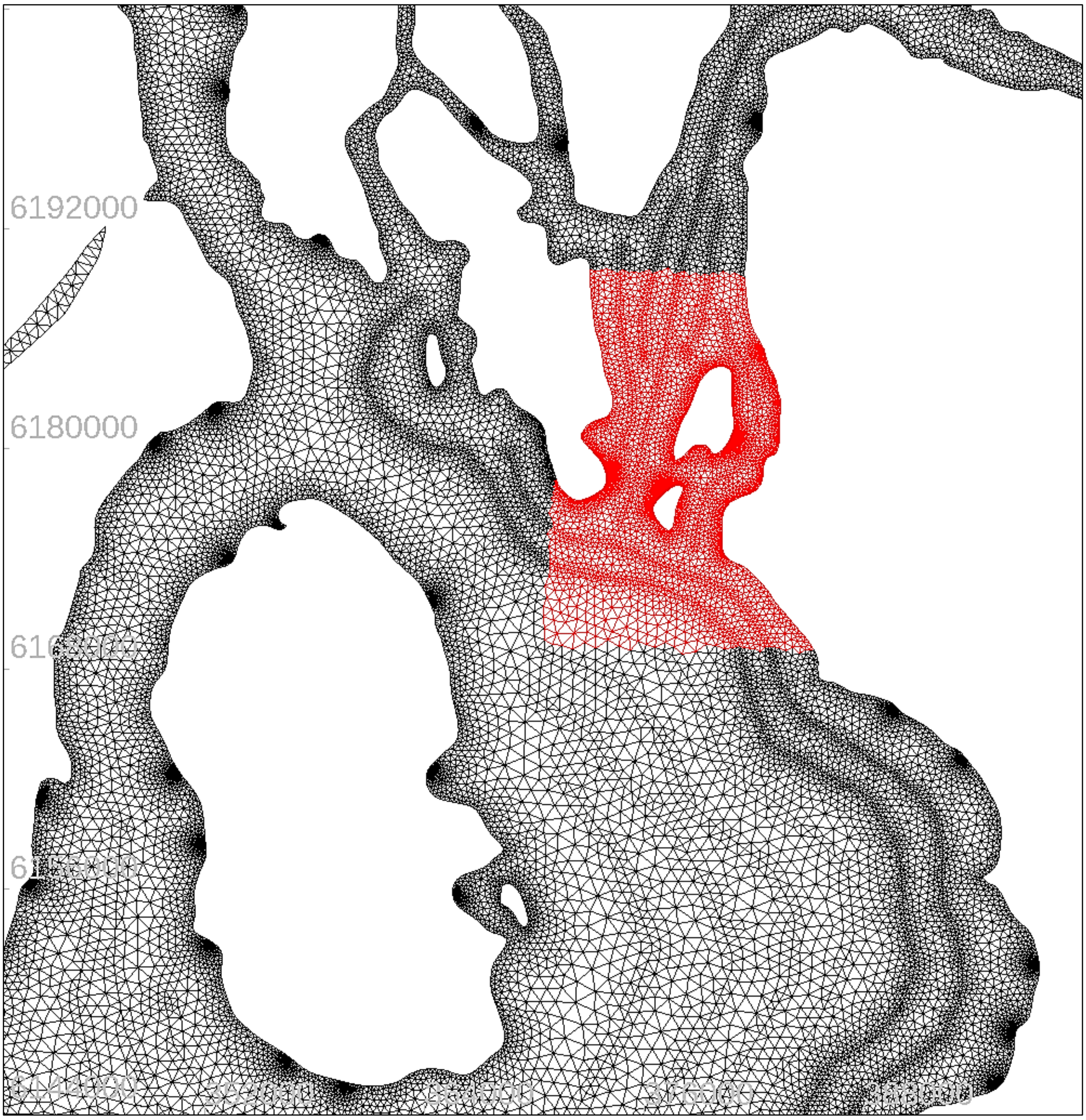

Figure 5 *Zoomed view of the original Telemac 3D hydrodynamics mesh (38.2 Gb, black) and the reduced size model (3.1 Gb, red). Denser mesh areas on the coastline show approximate river inlet locations.*

2.4 *Bathymetry data*

The bathymetry data for the present study have been collected from a range of different sources including publicly available data sets provided by Marine Scotland for the Scottish Shelf Model [SSM, 2023], digitised Admiralty charts and bathymetry information from the UK’s Digimap Ordnance Survey Collection [DOSC, 2023]. The bathymetry used in the model is shown in Figure 6.

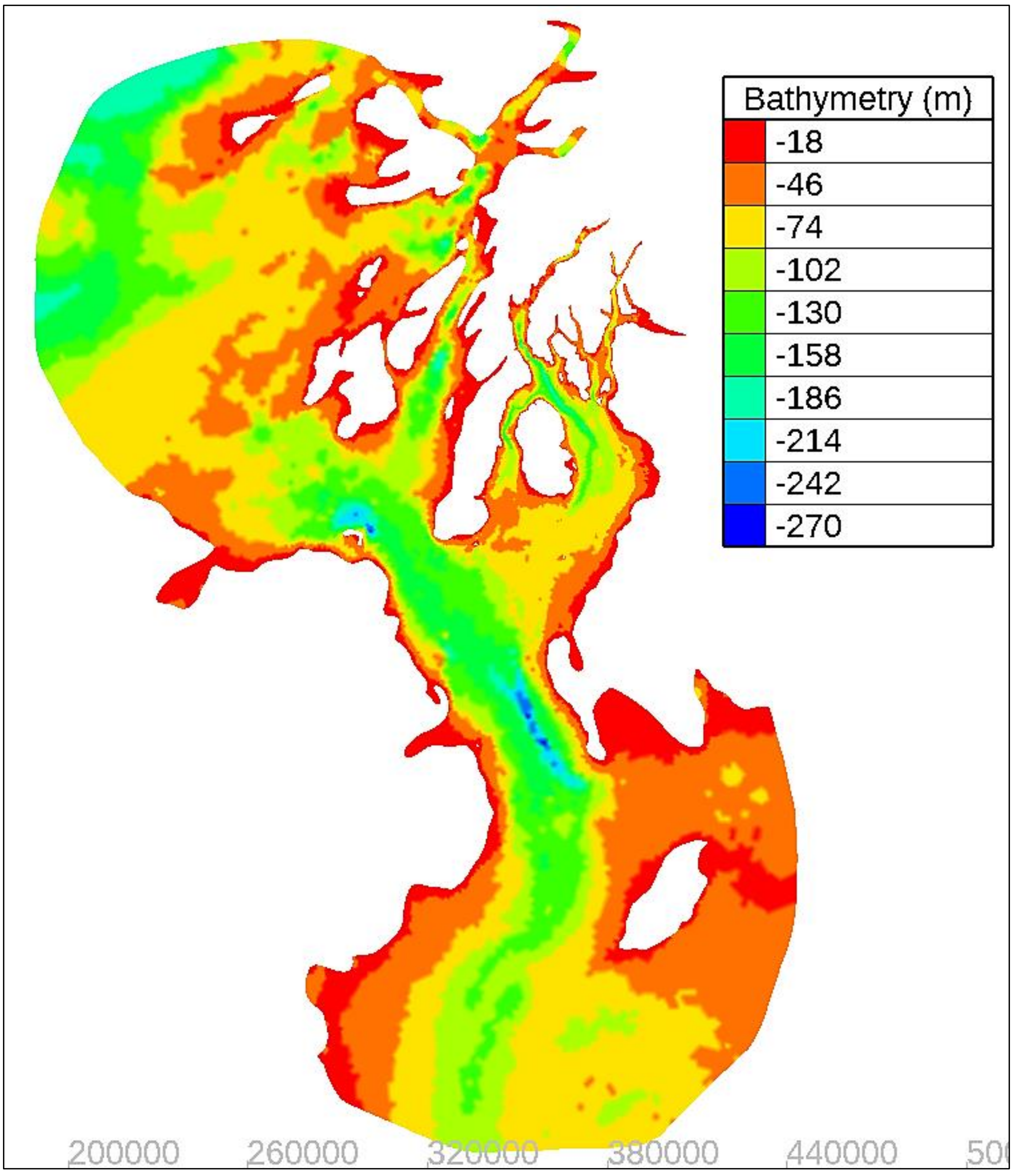

Figure 6 *West coast and Firth of Clyde bathymetry (m).*

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 $d2 = 1$ 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 observed and modelled data [CLAWS, 2023]. The measuring point corresponds to that shown in Figure 1 and three Excel spreadsheets were used which describe the physical measurements of sea surface height (SSH, m), current speed (m/s) and direction (deg) at depths corresponding to near-bed, mid-height and near surface. For further details see the relevant Excel spreadsheet.

3.1 Near-surface results (Excel Spreadsheet: *Little Cumbrae 90 days Sur HG*)

At the near-surface measurement location, the sea surface height was reasonably accurately modelled, with model skill of 0.97 (Figure 7 and Table 1). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.25 m and 0.31 m, respectively, are about 7.7% and 9.6% of the spring tide range, respectively. North and east components of velocity at the measurement location were satisfactorily reproduced by the model, both having values of the model skill, d2, of 0.67. The values of the MAE and RMSE being in the range 6 – 9 cm s^{-1} (Table 1). Table 2 shows the comparison of modelled sea surface height, current direction and timing of high water compared with the SEPA acceptable range [SEPA, 2019]. The Telemac model data are generally in satisfactory agreement with the SEPA standards, except for a slight over-prediction of the high-water timing. The scatter plots and histograms shown in Figures 8-12 demonstrate that the modelled currents were broadly of the same speed and direction as the observed data.

Table 1. Model performance statistics for sea surface height (SSH), and East and North velocity at the Little Cumbrae near-surface measurement location from 4th-26th October 2017.

	SSH	East	North
Skill, d2	0.97	0.67	0.67
Mean Absolute Error (MAE)	0.25	0.07 m/s	0.06 m/s
Root-Mean-Square Error (RMSE)	0.31	0.09 m/s	0.08 m/s

Table 2. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH), current direction (based on residual flow) and timing of high water at the Little Cumbrae near-surface measurement location from 4th-26th October 2017.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	9.6 %	✓
Current speed	+/- 0.1 m/s	0.08 m/s	✓
Current speed	+/- 10-20 %	15.9 %	✓
Current direction	+/- 30 deg	16.8 deg	✓
Timing of high water / phase	+/- 15 mins	18 mins	✗

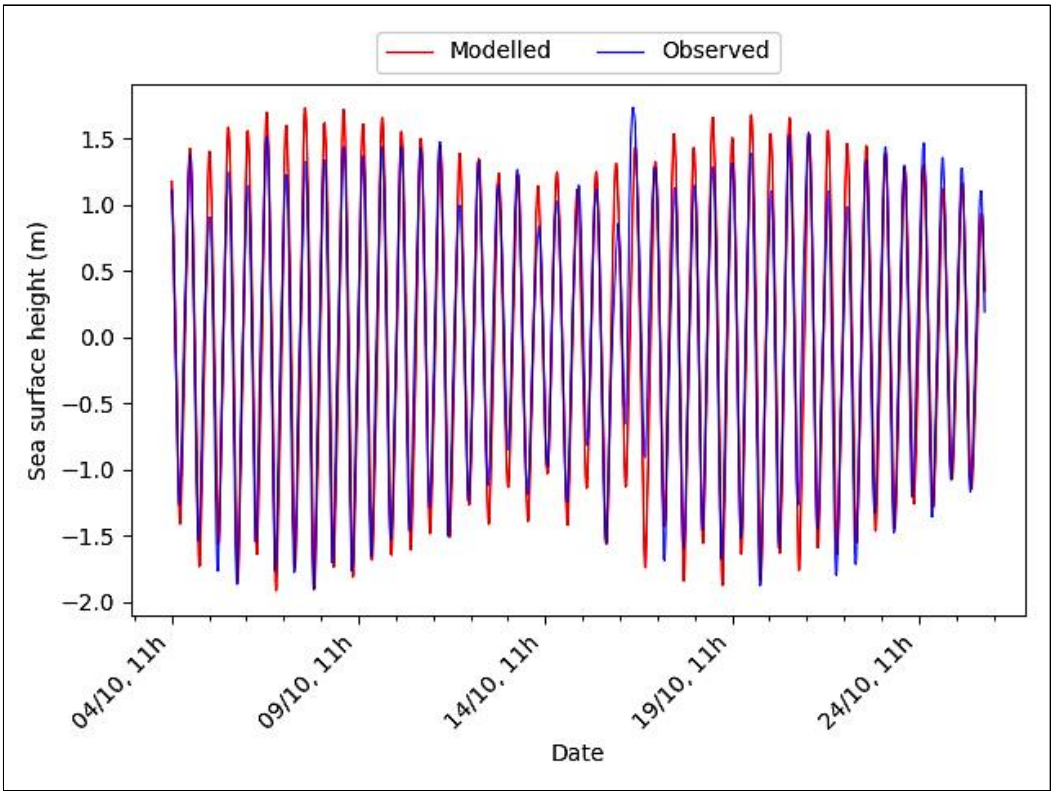

Figure 7 *Comparison between observed and modelled sea surface height from 4th-26th October 2017 (near-surface measurement point – see Figure 1).*

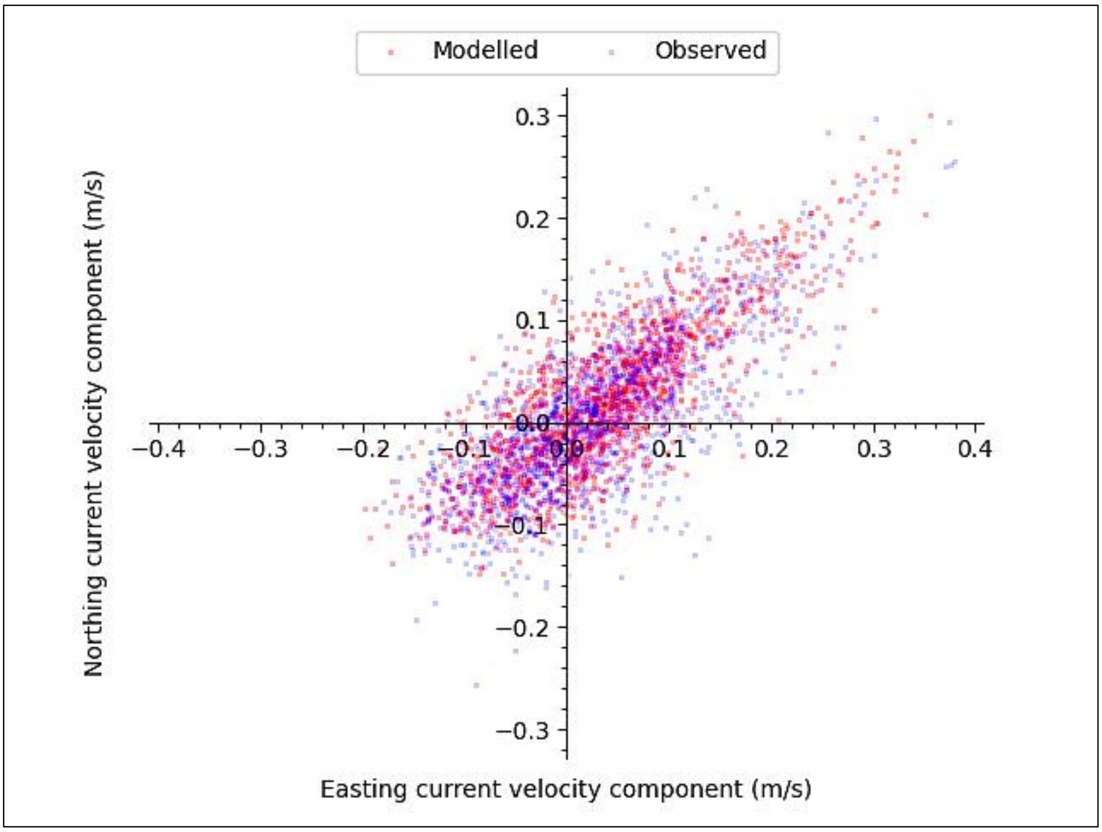

Figure 8 *Scatter plot of observed and modelled velocity from 4th-26th October 2017 (near-surface measurement point – see Figure 1).*

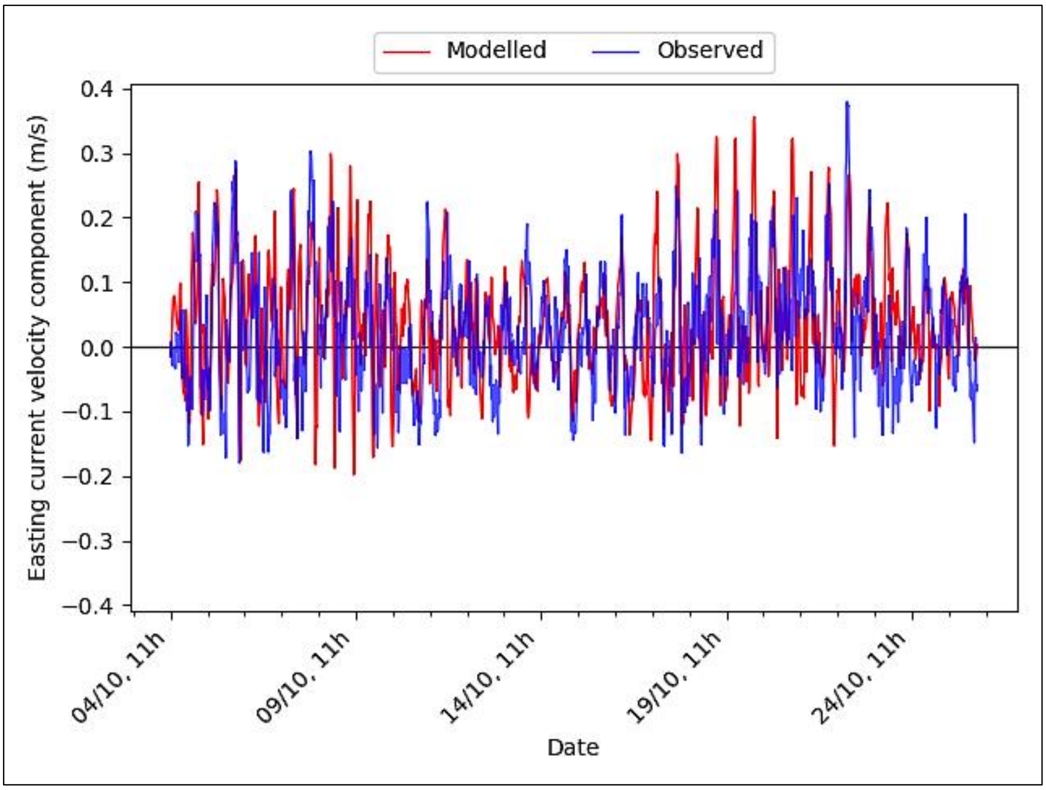

Figure 9 *Comparison between observed and modelled East velocity component from 4th-26th October 2017 (near-surface measurement point – see Figure 1).*

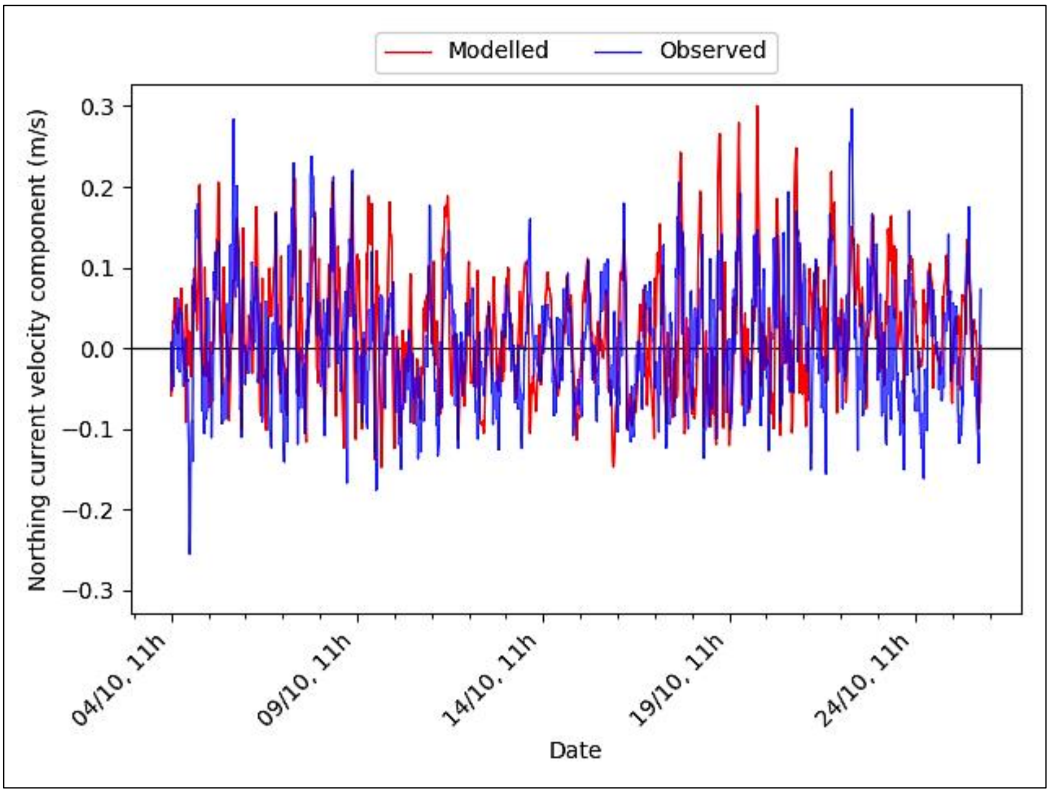

Figure 10 *Comparison between observed and modelled North velocity component from 4th-26th October 2017 (near-surface measurement point – see Figure 1).*

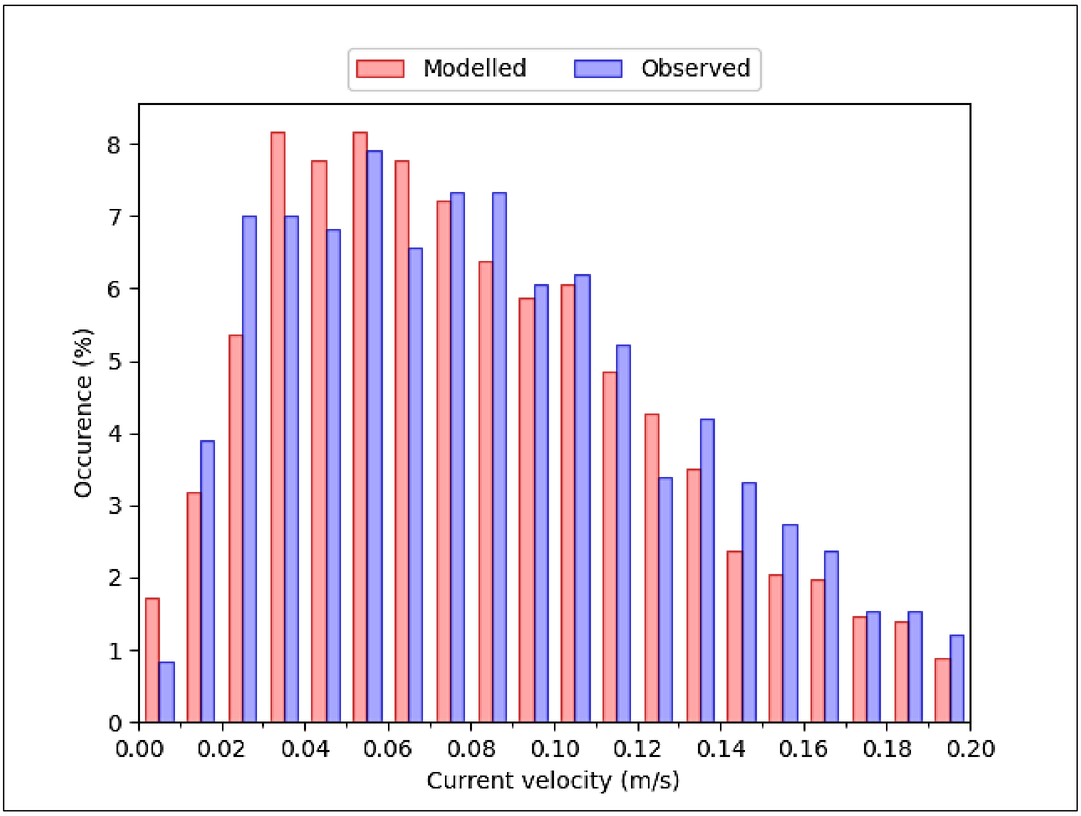

Figure 11 *Histogram of observed and modelled current speed component from 4th-26th October 2017 (near-surface measurement point – see Figure 1). Model skill d2 = 0.97.*

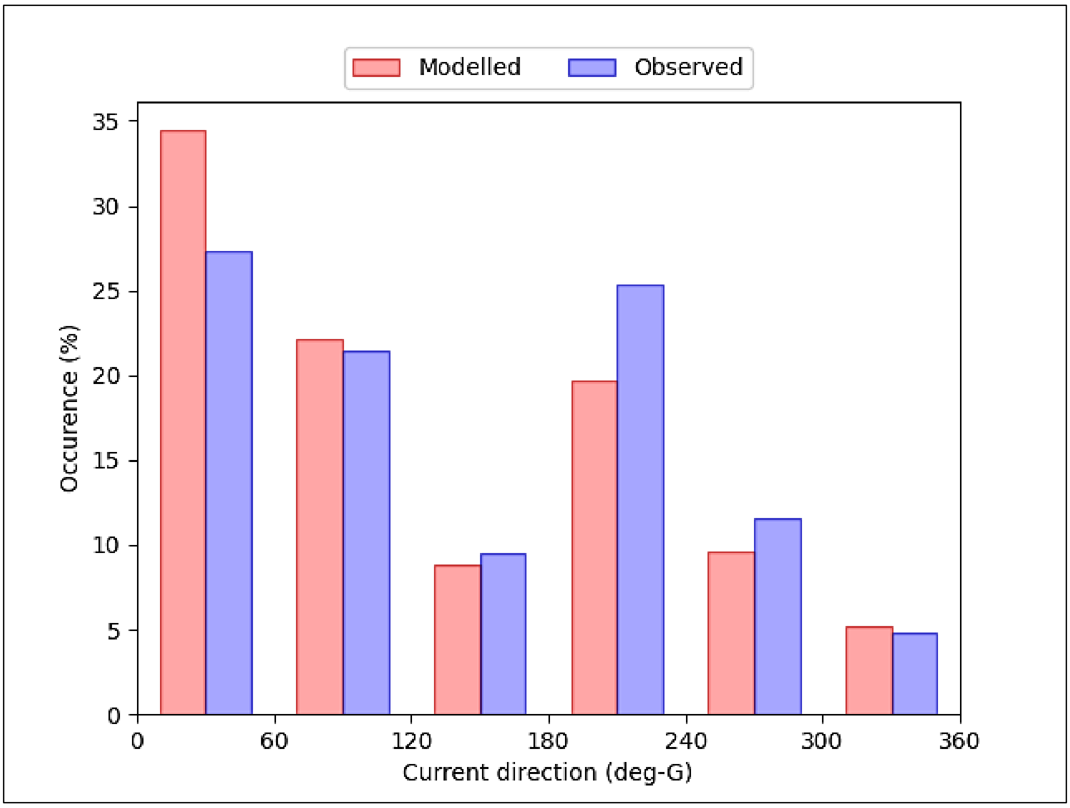

Figure 12 *Histogram of observed and modelled current direction from 4th-26th October 2017 (near-surface measurement point – see Figure 1). Model skill d2 = 0.96.*

3.2 Mid-height results (Excel Spreadsheet: *Little Cumbrae 90 days Mid HG*)

At the mid-height measurement location, the sea surface level was reasonably accurately modelled, with model skill of 0.97 (Figure 13 and Table 3). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.25 m and 0.31 m, respectively, are about 7.7% and 9.6% of the spring tide range, respectively. East and north components of velocity at the measurement location were satisfactorily reproduced by the model, having values of the model skill, d2, of 0.68 and 0.69, respectively. The values of the MAE and RMSE being in the range 5 – 8 cm s^{-1} (Table 3). Table 4 shows the comparison of modelled sea surface height, current direction and timing of high water compared with the SEPA acceptable range [SEPA, 2019]. The Telemac model data are generally in satisfactory agreement with the SEPA standards, except for a slight over-prediction of the high-water timing. The scatter plots and histograms shown in Figures 13-18 demonstrate that the modelled currents were broadly of the same speed and direction as the observed data.

Table 3. Model performance statistics for sea surface height (SSH), and East and North velocity at the Little Cumbrae mid-height measurement location from 4th-26th October 2017.

	SSH	East	North
Skill, d2	0.97	0.68	0.69
Mean Absolute Error (MAE)	0.25	0.06 m/s	0.05 m/s
Root-Mean-Square Error (RMSE)	0.31	0.08 m/s	0.06 m/s

Table 4. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH), current direction (based on residual flow) and timing of high water at the Little Cumbrae mid-height measurement location from 4th-26th October 2017.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	9.6 %	✓
Current speed	+/- 0.1 m/s	0.06 m/s	✓
Current speed	+/- 10-20 %	19.7 %	✓
Current direction	+/- 30 deg	19.0 deg	✓
Timing of high water / phase	+/- 15 mins	18 mins	×

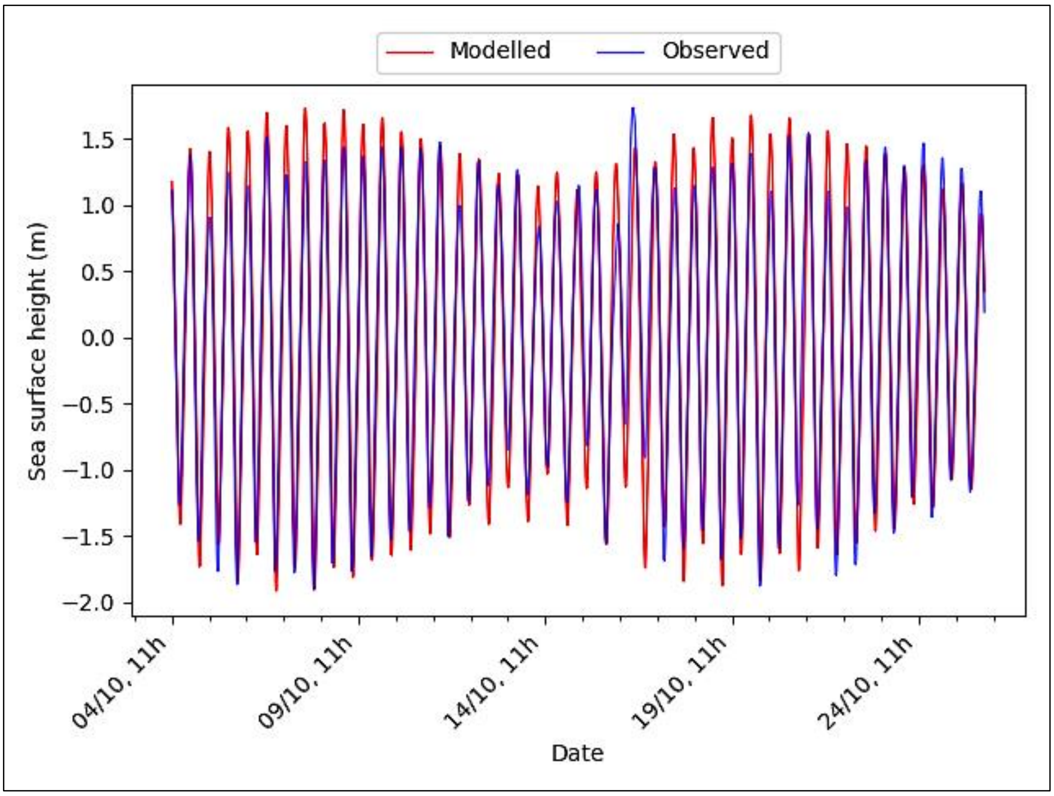

Figure 13 *Comparison between observed and modelled sea surface height from 4th-26th October 2017 (mid-height measurement point – see Figure 1).*

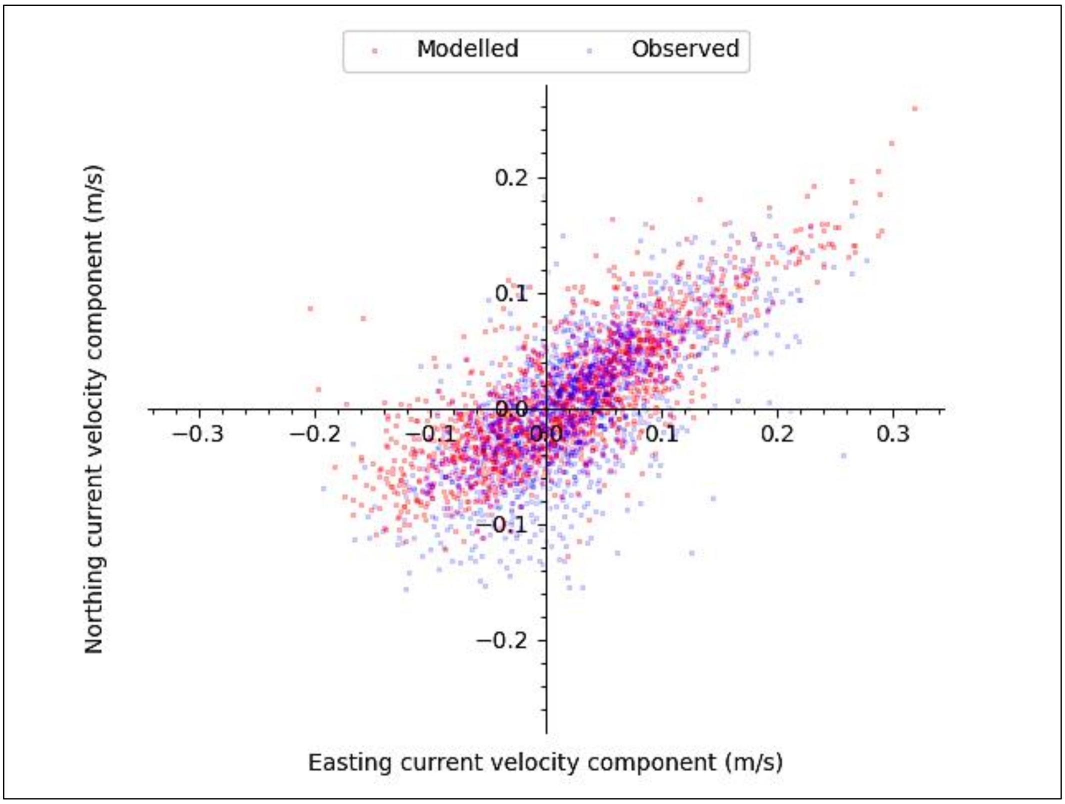

Figure 14 *Scatter plot of observed and modelled velocity from 4th-26th October 2017 (mid-height measurement point – see Figure 1).*

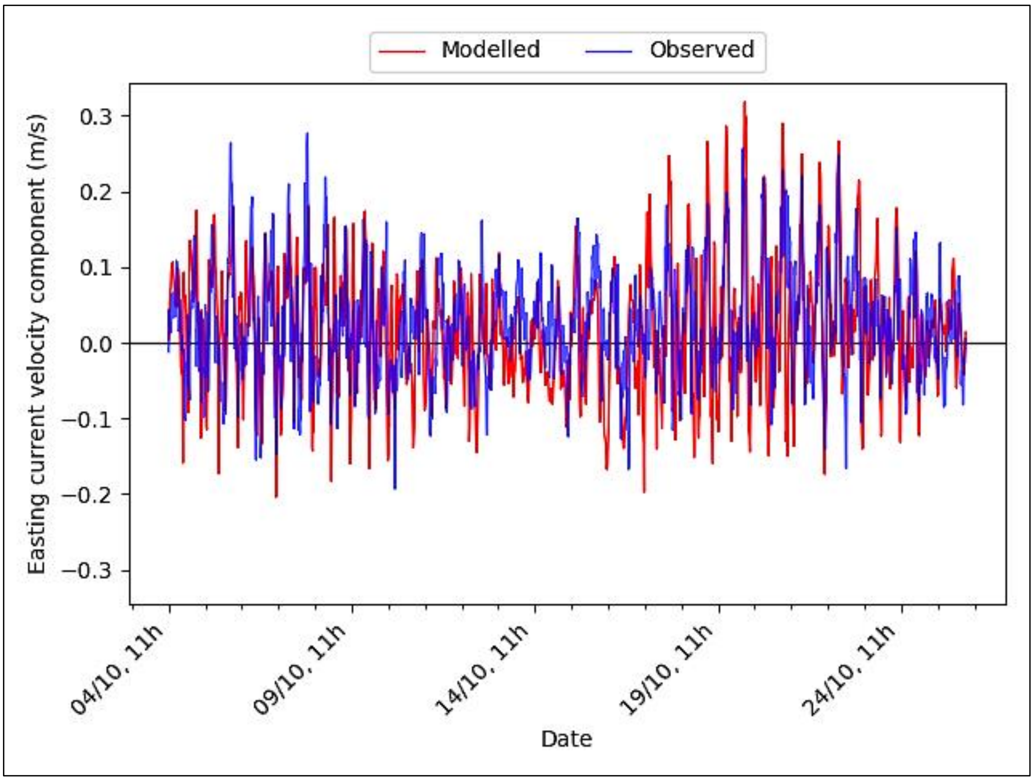

Figure 15 *Comparison between observed and modelled East velocity component from 4th-26th October 2017 (mid-height measurement point – see Figure 1).*

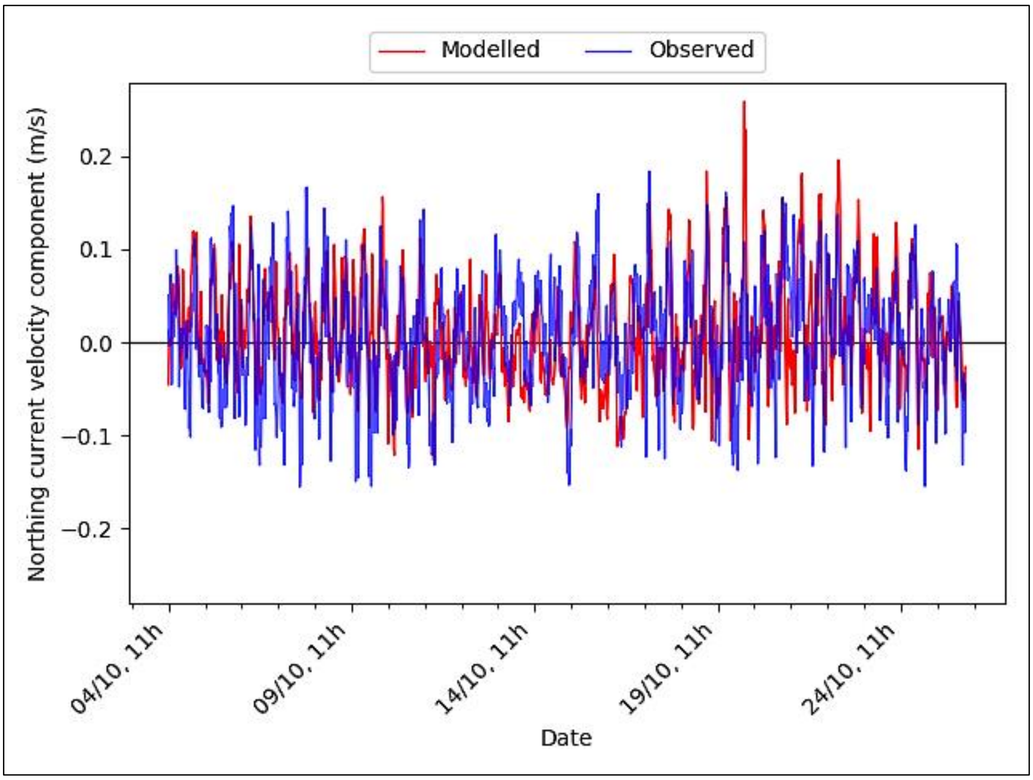

Figure 16 *Comparison between observed and modelled North velocity component from 4th-26th October 2017 (mid-height measurement point – see Figure 1).*

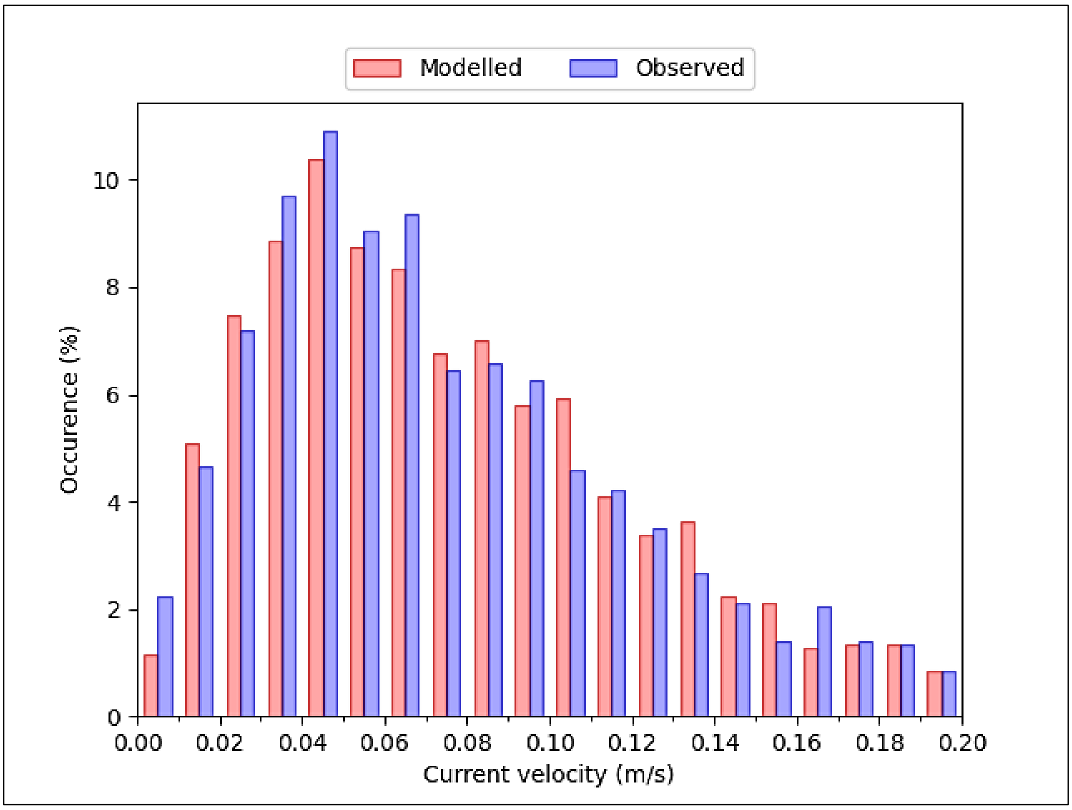

Figure 17 *Histogram of observed and modelled current speed component from 4th-26th October 2017 (mid-height measurement point – see Figure 1). Model skill d2 = 0.99.*

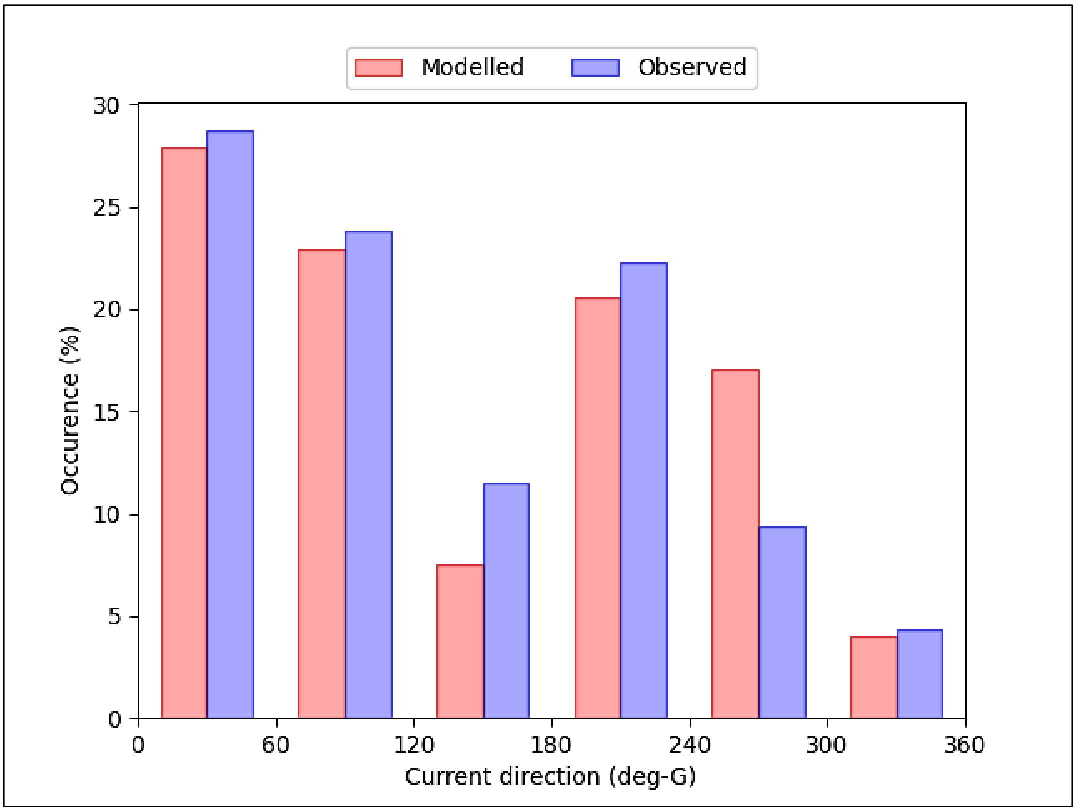

Figure 18 *Histogram of observed and modelled current direction from 4th-26th October 2017 (mid-height measurement point – see Figure 1). Model skill d2 = 0.95.*

3.3 Near-bottom results (Excel Spreadsheet: *Little Cumbrae 90 days Bot HG*)

At the near-bottom measurement location, the sea surface level was reasonably accurately modelled, with model skill of 0.97 (Figure 19 and Table 5). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.25 m and 0.31 m, respectively, are about 7.7% and 9.6% of the spring tide range, respectively. North and east components of velocity at the measurement location were reasonably well reproduced by the model, having values of the model skill, d2, of 0.48 and 0.54, respectively. The values of the MAE and RMSE being in the range 4 – 8 cm s^{-1} (Table 5). Table 6 shows the comparison of modelled sea surface height, current direction and timing of high water compared with the SEPA acceptable range [SEPA, 2019]. The Telemac model data are generally in satisfactory agreement with the SEPA standards, except for a slight over-prediction of the high-water timing. The scatter plots and histograms shown in Figures 19-24 demonstrate that the modelled currents were broadly aligned with speed and direction found in the observed data.

Table 5. Model performance statistics for sea surface height (SSH), and East and North velocity at the Little Cumbrae near-bottom measurement location from 4th-26th October 2017.

	SSH	East	North
Skill, d2	0.97	0.54	0.48
Mean Absolute Error (MAE)	0.25	0.06 m/s	0.04 m/s
Root-Mean-Square Error (RMSE)	0.31	0.08 m/s	0.05 m/s

Table 6. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH), current direction (based on residual flow) and timing of high water at the Little Cumbrae near-bottom measurement location from 4th-26th October 2017.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	9.6 %	✓
Current speed	+/- 0.1 m/s	0.06 m/s	✓
Current speed	+/- 10-20 %	19.4 %	✓
Current direction	+/- 30 deg	27.3 deg	✓
Timing of high water / phase	+/- 15 mins	18 mins	✗

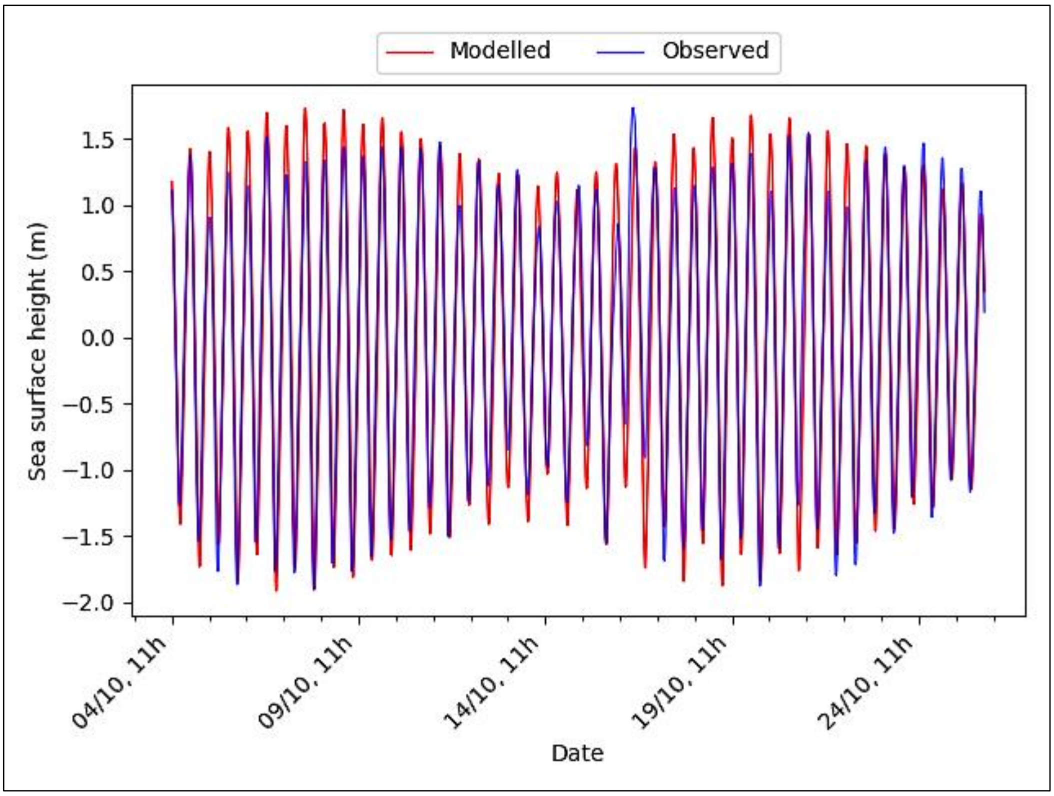

Figure 19 *Comparison between observed and modelled sea surface height from 4th-26th October 2017 (near-bottom measurement point – see Figure 1).*

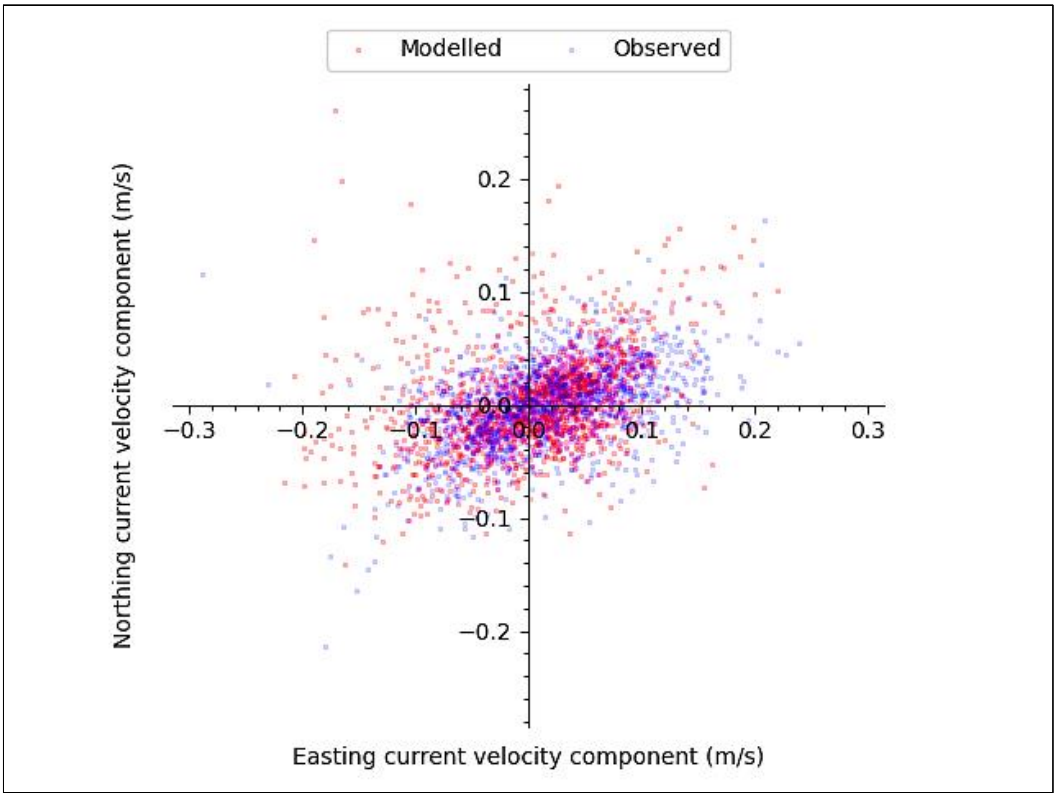

Figure 20 *Scatter plot of observed and modelled velocity from 4th-26th October 2017 (near-bottom measurement point – see Figure 1).*

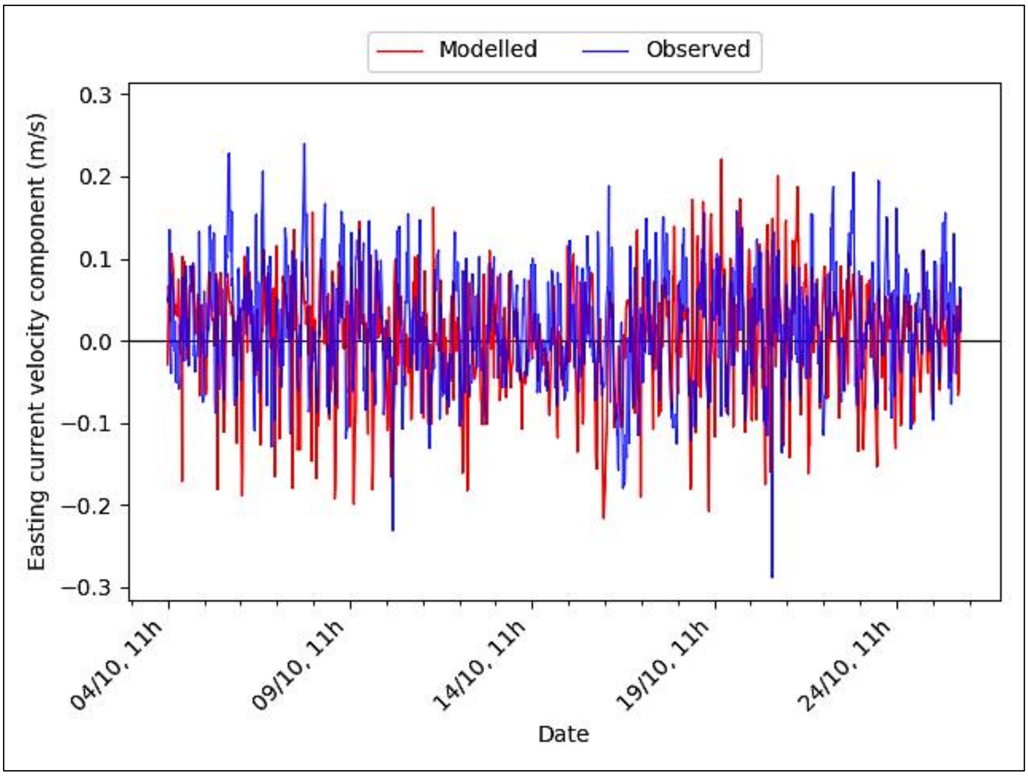

Figure 21 *Comparison between observed and modelled East velocity component from 4th-26th October 2017 (near-bottom measurement point – see Figure 1).*

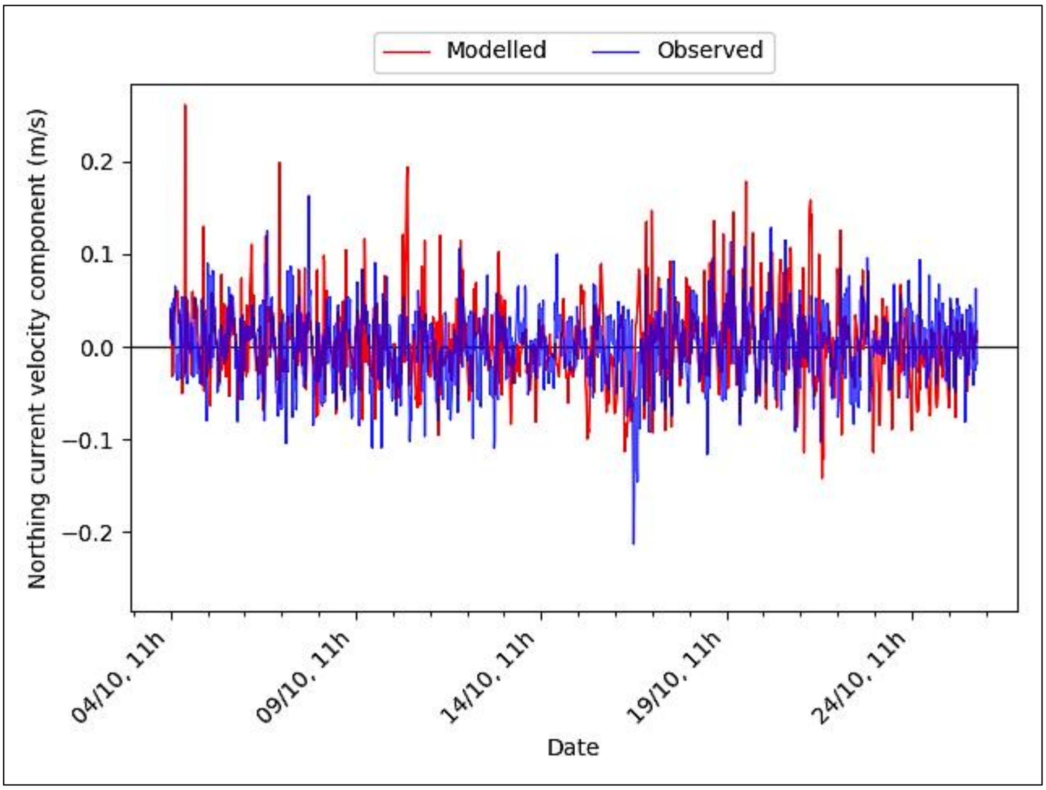

Figure 22 *Comparison between observed and modelled North velocity component from 4th-26th October 2017 (near-bottom measurement point – see Figure 1).*

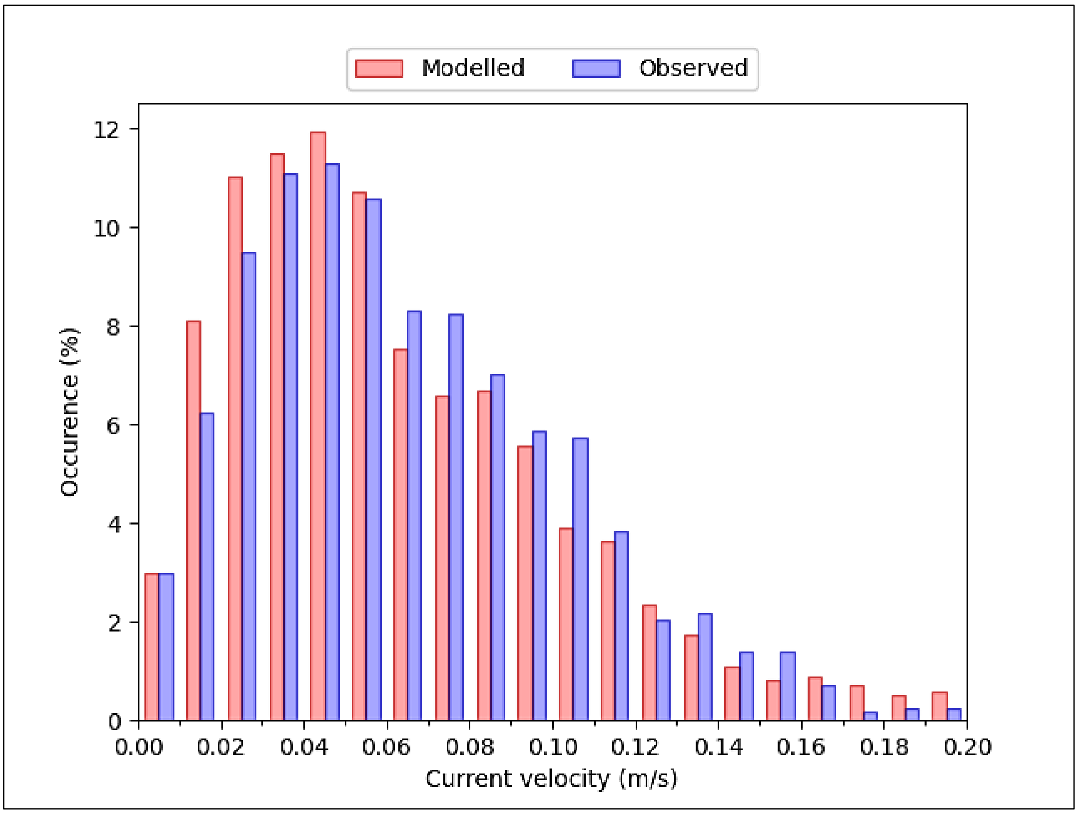

Figure 23 *Histogram of observed and modelled current speed component from 4th-26th October 2017 (near-bottom measurement point – see Figure 1). Model skill d2 = 0.99.*

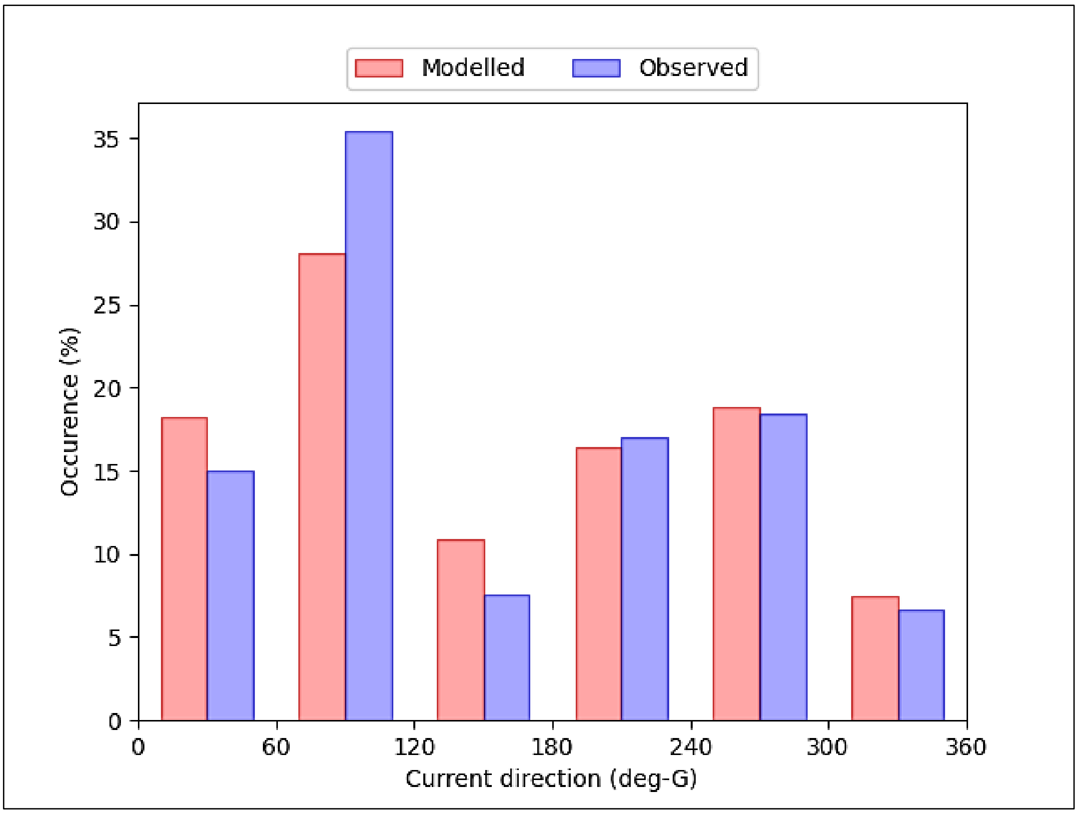

Figure 24 *Histogram of observed and modelled current direction from 4th-26th October 2017 (near-bottom measurement point – see Figure 1). Model skill d2 = 0.95.*

It is noted that the skill scores and error estimates from the Telemac model output are comparable in magnitude to previously published data for hydrodynamics on the West Coast of Scotland [MOWI_A, 2021].

Further examples of the CLAWS Python script output are provided in Appendix A for information.

4. Modelled Flow Fields in the Firth of Clyde around Little Cumbrae

Modelled velocity vectors in the vicinity of Little Cumbrae are shown in Figures 25 and 26. The area around the Cumbraes is subject to tidal currents flowing in and out of the Firth of Clyde system with the principal fresh water source coming from the river Clyde. The magnitude and direction of these currents are seen to vary with depth. The highly three-dimensional nature of the flow is due to the complex interactions of fresh and salt water and weather-driven effects in the estuarial system. The less-dense, brackish water in the surface layers is observed to often have a different magnitude and flow direction (Figure 25) compared to the deeper, more saline water (Figure 26).

In the surface layers, a counter-clockwise vortex is seen to form off the north-west corner of Little Cumbrae (Figure 25), however, this is less evident in the near-bed layers and the flow is actually reversed, following a north-east trajectory (Figure 26). Other zones where significant flow reversal is evident include the area to the east of Little Cumbrae where the near-bed currents are seen to follow a north-east path, in contrast to the near-surface velocities.

These images serve to highlight the complex, three-dimensional nature of the flows in the Firth of Clyde. A non-hydrostatic, 3D modelling approach such as the one adopted in this study is likely to be the most effective way of capturing such physical features. This is particularly important when the hydrodynamic fields are used to drive other particle-based models as the depth-varying nature of the flow can influence the overall distribution of bath treatment pesticides, nutrients, solid waste and salmon lice.

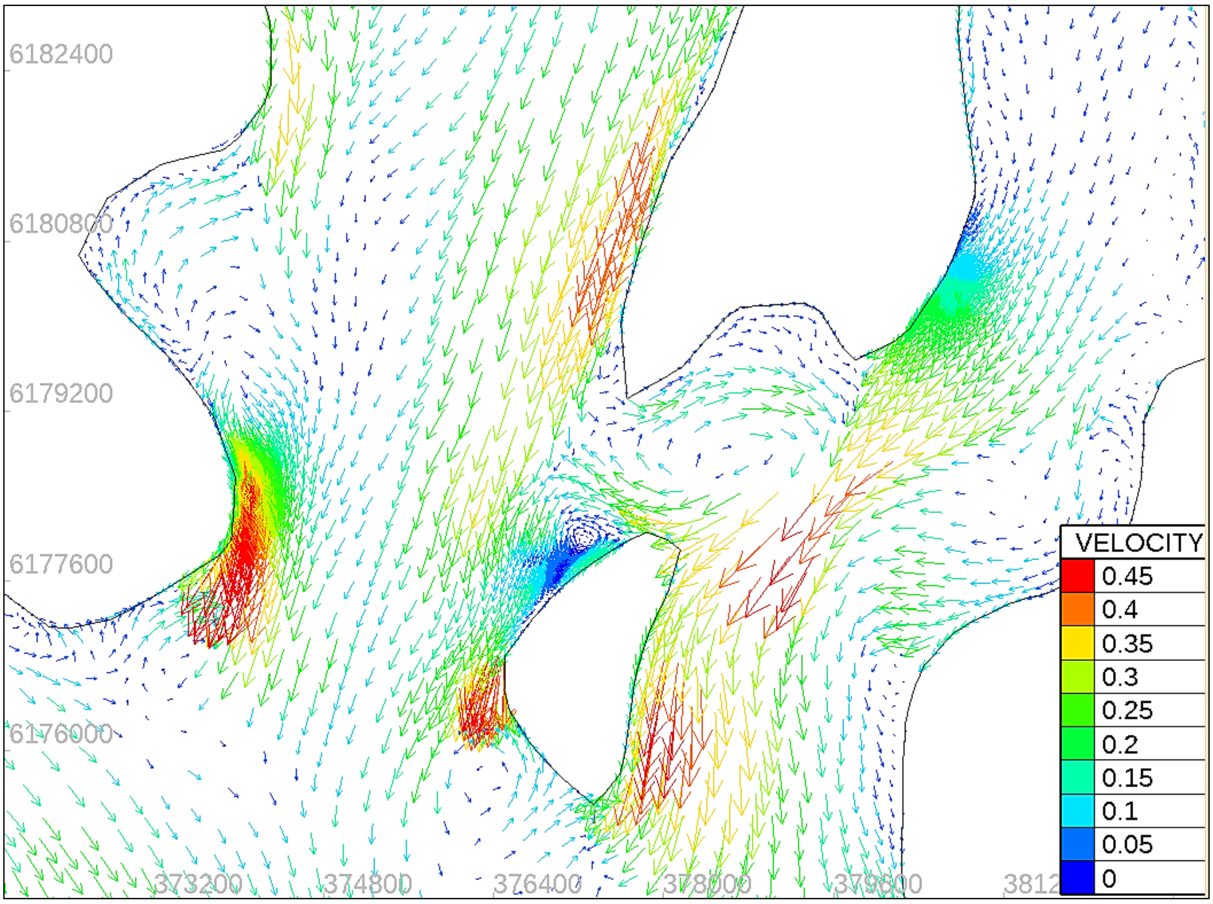

Figure 25 *Velocity vectors (m/s) in the near-surface layer around Little Cumbrae on the 25th October 2017 at 08h40.*

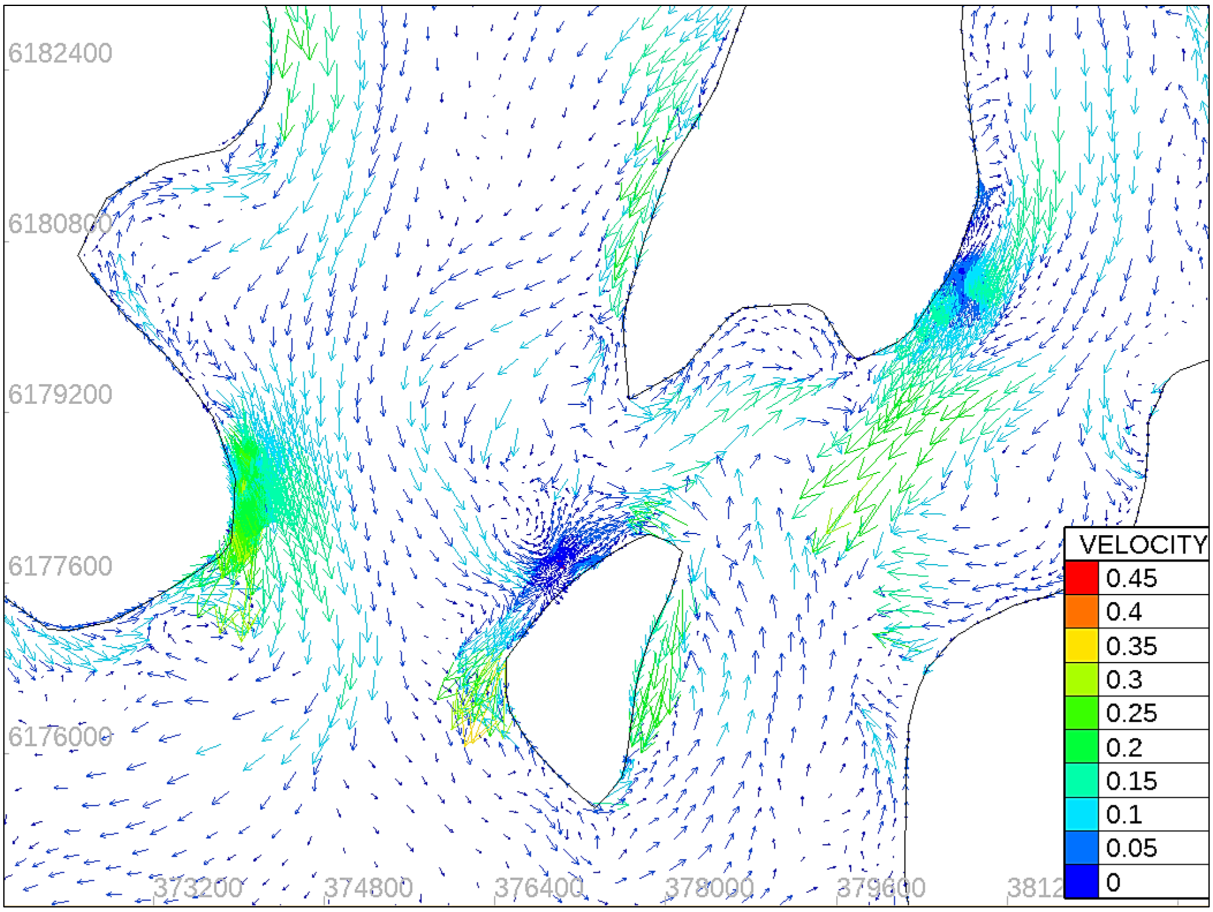

Figure 26 *Velocity vectors (m/s) in the near-sea bed layer around Little Cumbrae on the 25th October 2017 at 08h40.*

5. Conclusions

Python scripts have been written to allow the direct comparison of observed and modelled hydrodynamic data as part of open source platform CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS, 2023]. The hydrodynamic model of the Firth of Clyde, generated using the Telemac3D software, correctly simulates the propagation of the tide over the West Coast of Scotland with a focus on the Firth of Clyde. The modelling approach provides a reasonable description of the flows within the Clyde system in terms of current magnitude and direction. In general, the model data compares favourably against the SEPA calibration/validation requirements for hydrodynamic and discharge modelling [SEPA, 2019]. The flow in the Clyde estuary around Little Cumbrae is shown to exhibit strong three-dimensionality with the competing effects of tides, winds, salinity and temperature evident.

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APPENDIX A

Further CLAWS Python script output from the hydrodynamic data set.

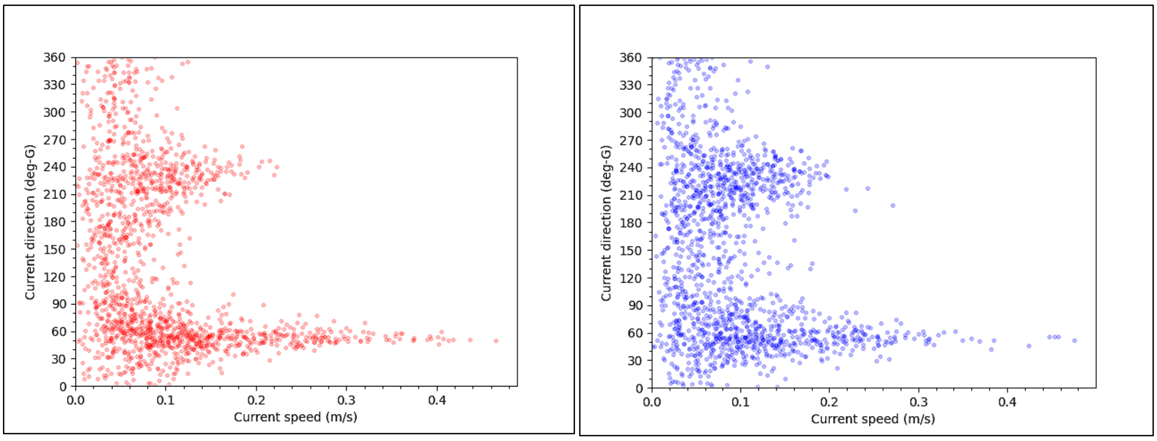

Figure A.1 *Current speed (m/s) versus direction (deg) for the near-surface measurement point. Telemac model (left) and observation (right).*

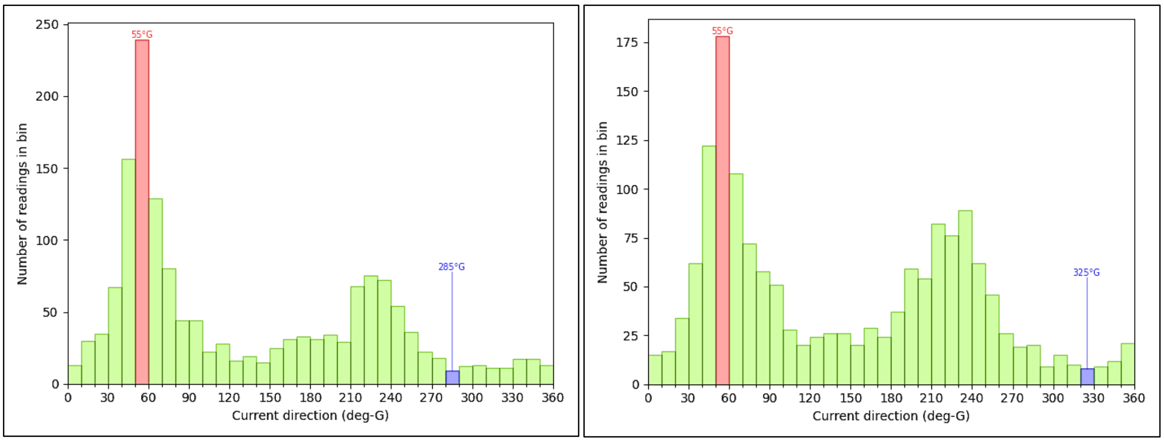

Figure A.2 *Current direction bar graph (deg) for the near-surface measurement point. Telemac model (left) and observation (right).*

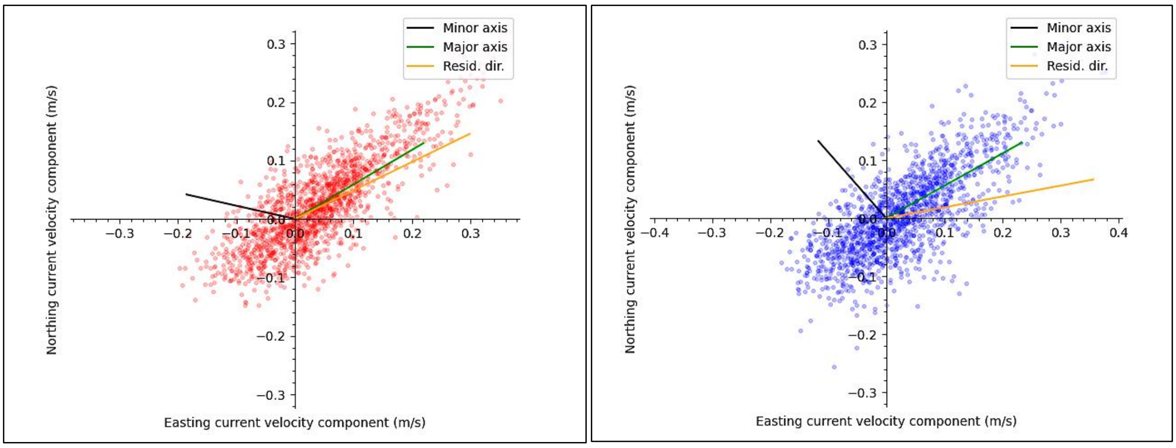

Figure A.3 *Easting versus northing velocity component (m/s) for the near-surface measurement point. Telemac model (left) and observation (right).*

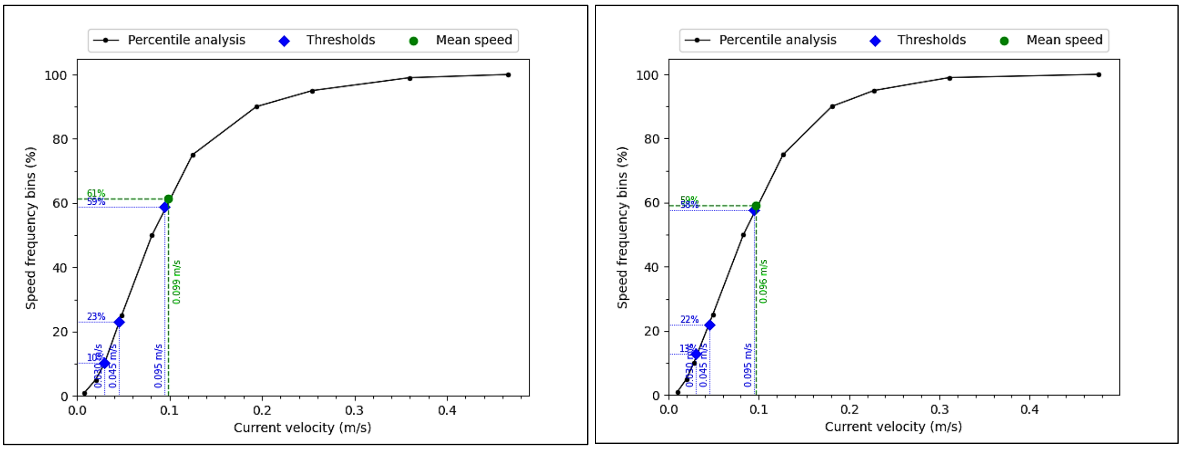

Figure A.4 *Current speed (m/s) percentile analysis for the near-surface measurement point. Telemac model (left) and observation (right).*

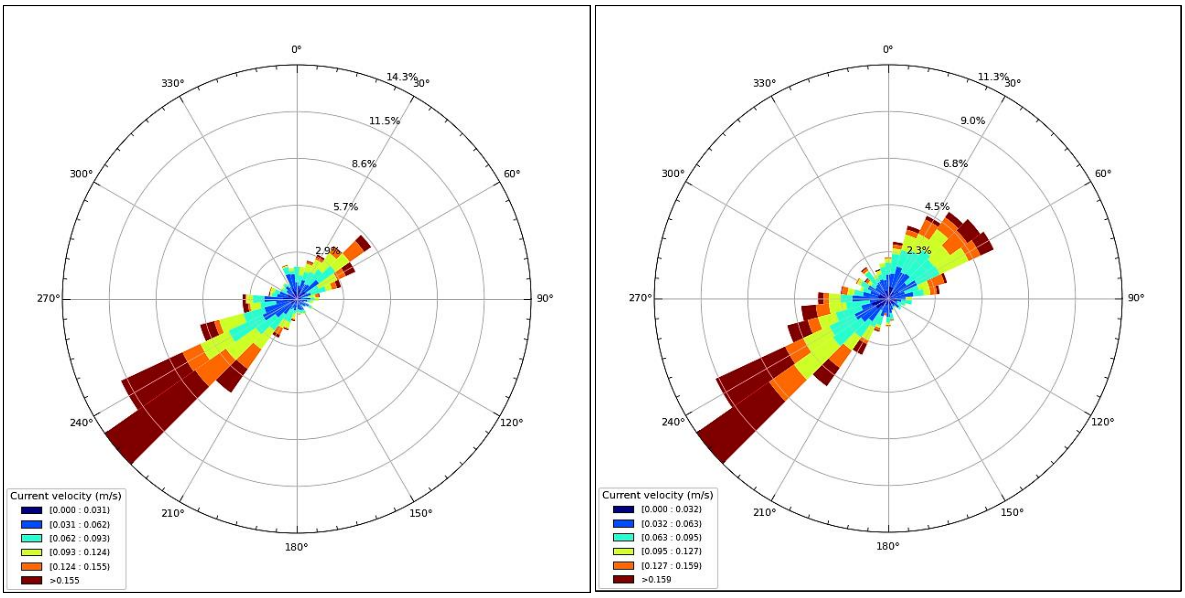

Figure A.5 *Filled wind rose of current velocity (m/s) for the near-surface measurement point. Telemac model (left) and observation (right).*