Orkney and Shetland Hydrodynamics Model Validation

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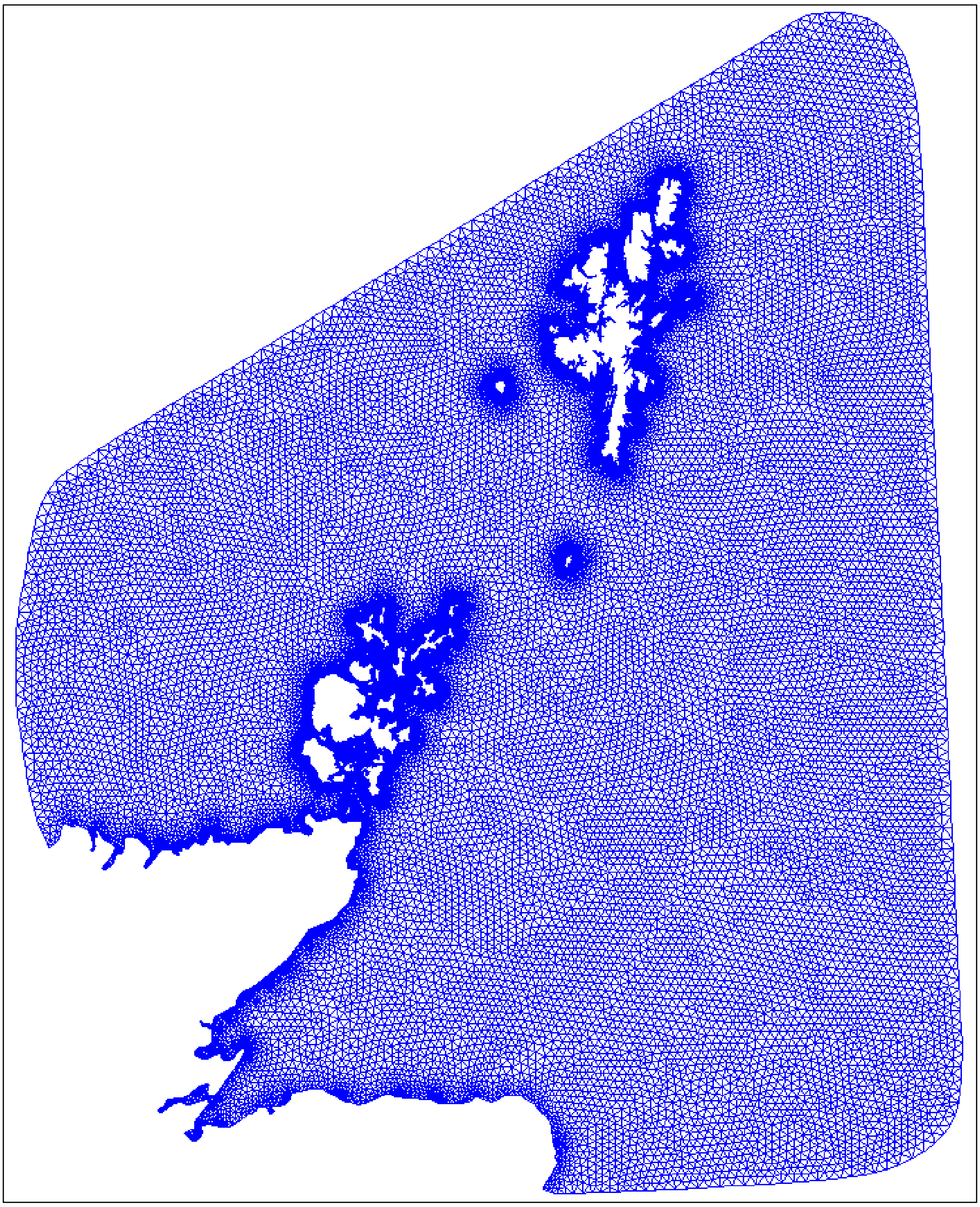

Executive Summary

A three-dimensional hydrodynamic (HD) model of the Northern Isles has been constructed using the Telemac code [TELEMAC, 2024]. The 3D model extends from Cape Wrath, arcing clockwise around Orkney and Shetland to the Aberdeenshire coast. This report focuses on the validation of the model against physical observations across the region.

Tidally-driven oceanography in the area depicts a complex water circulation system, displaying various levels of density stratification and air-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 model 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 current speeds was included. The model also incorporated 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 in Orkney and Shetland, utilized data lifted from tide gauges and current surveys provided by SEPA.

The model correctly simulates tide propagation over the Northern Isles region, and its 3D approach reasonably describes flow currents in terms of magnitude and direction. Model data generally satisfy SEPA's calibration/validation requirements for hydrodynamic and discharge modelling [SEPA, 2019]. 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]. Other modules in the CLAWS toolbox cover pesticide treatments, dissolved nutrients, and solid particle feed waste.

The model provides general insight into spatial and temporal variations in the flow environment around Orkney, Shetland, and the North East coast of Scotland. It offers a suitable basis for modelling sea lice impact on wild salmon and sea trout, as well as assessing near-field and far-field dispersion effects of lice treatment pesticides, feed waste, and dissolved nutrients.

About the Report Author

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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 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.

1 Introduction and Motivation

This report has been prepared for Wildfish.org, 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 in the Northern isles.

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 a 3D hydrodynamic model to capture adequately the current patterns around Orkney and Shetland.

A 3D hydrodynamics approach based on the 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 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 for Lice and Waste from Salmon Farms [CLAWS, 2024]. Other modules in the CLAWS software suite include those for pesticide treatments, dissolved nutrients and solid particle feed waste.

2 Model Development

2.1 *Hydrodynamics*

The modelling approach employed the 3D non-hydrostatic version of Telemac across the North coast of Scotland and Northern isles, the extent of which is shown in Figures 1-4. 10 terrain-following vertical sigma layers are applied in the model and it includes tidal and meteorological forcing, stratification due to freshwater inflows and atmosphere-water heat exchange. Approximately 1.1 million elements were used in the model. Values of wind speed and direction at each validation site were provided by SEPA. Air temperature data were gathered from an online resource [TIME_DATE, 2024]. Extensive validation and verification tests have previously been undertaken for a similar model of the West coast of Scotland against physical data and inter-model comparisons with the Scottish Shelf Model [SSM, 2024] results, for further details see [SCANLON, 2022].

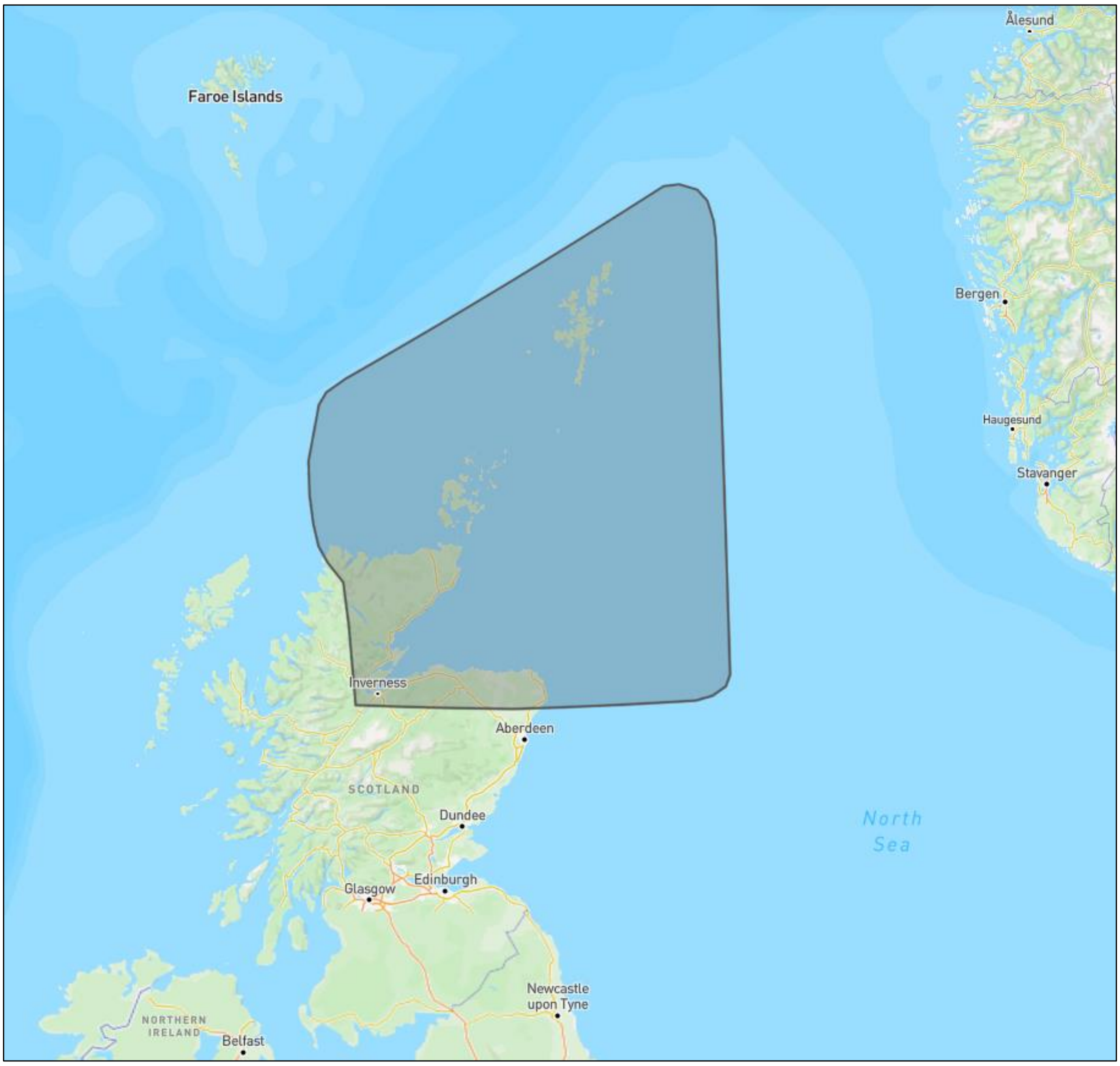

Figure 1 *Polygon used to create Telemac 3D hydrodynamic mesh (see Fig. 2).*

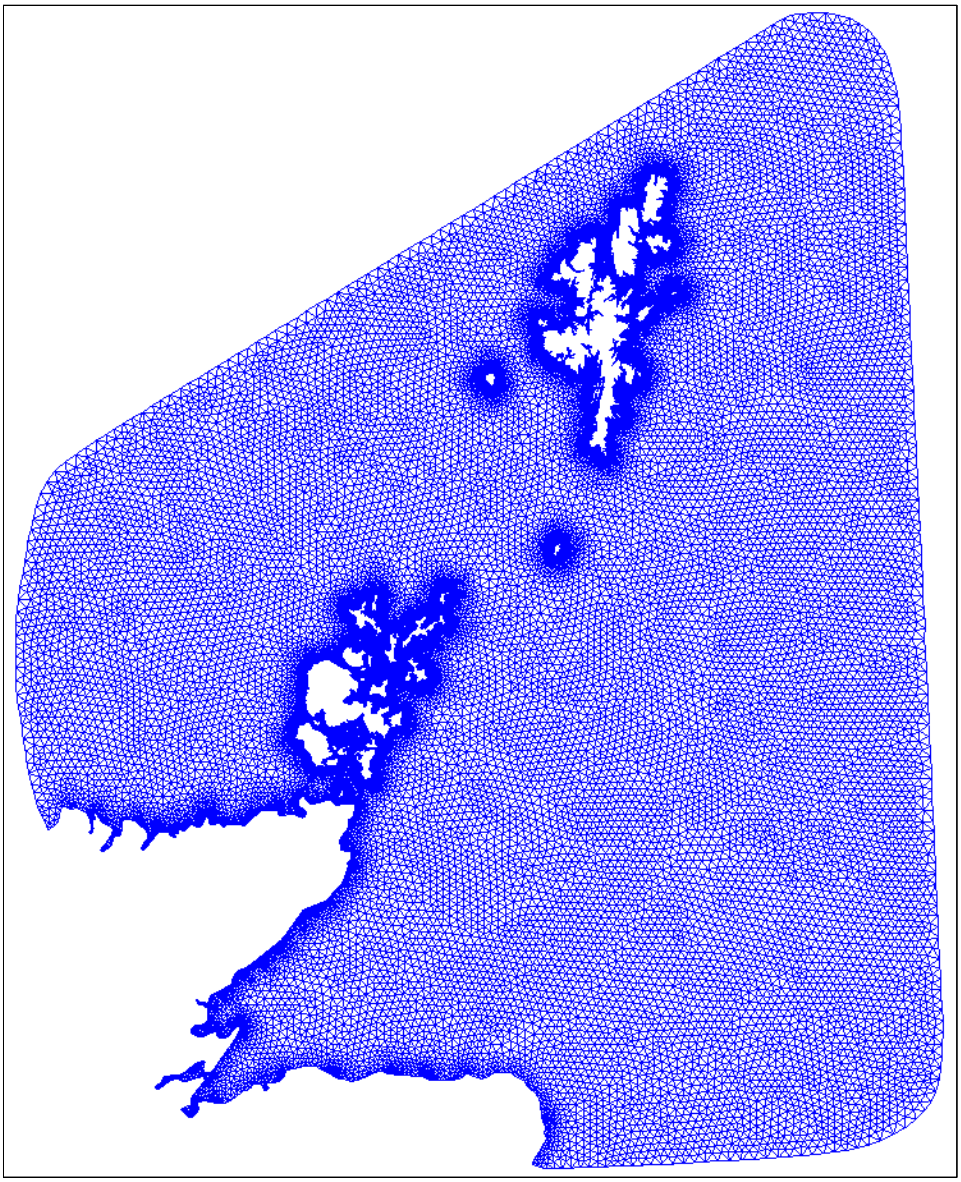

Figure 2 *Telemac 3D hydrodynamic mesh and model extent.*

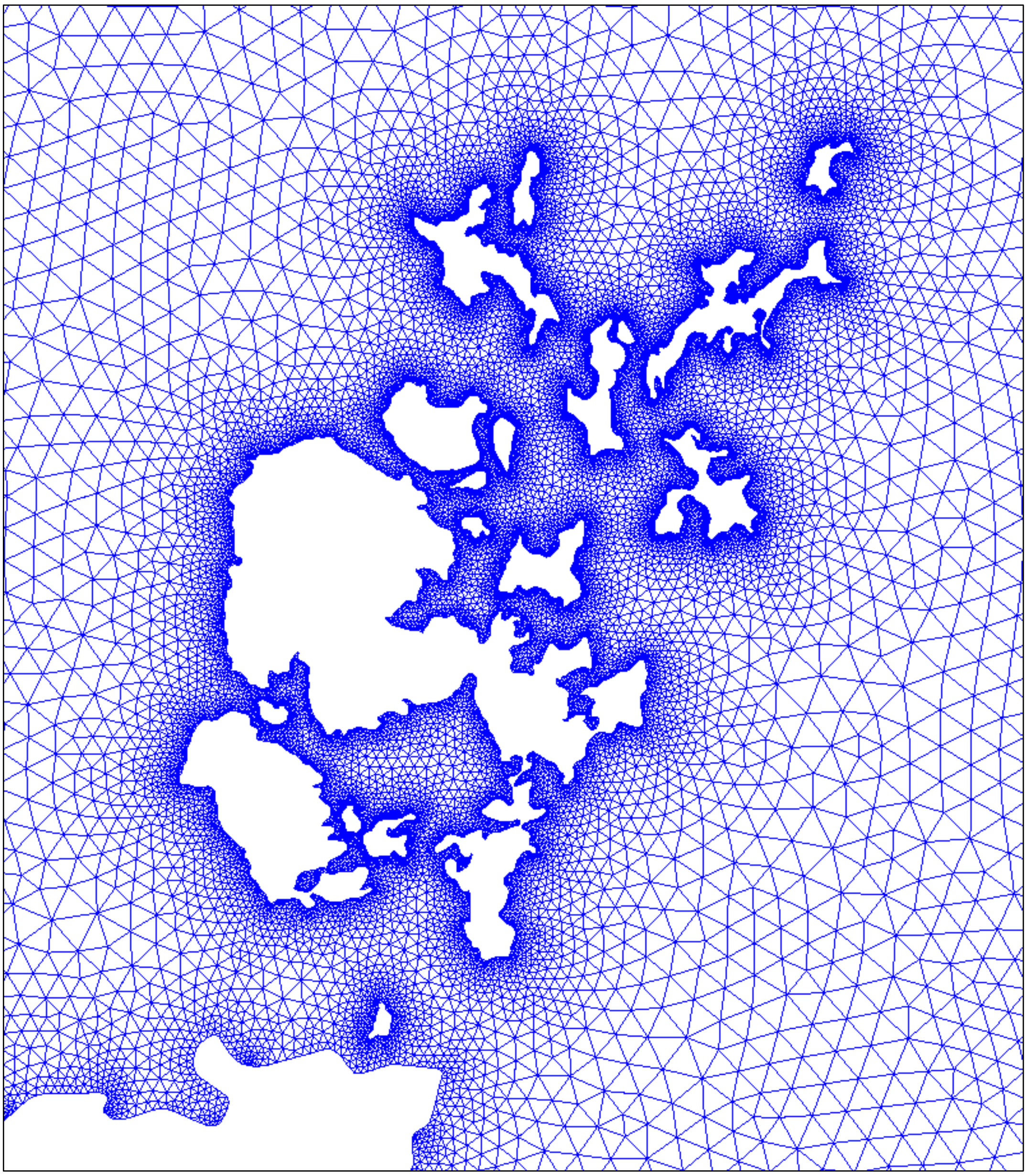

Figure 3 *Hydrodynamic mesh around Orkney.*

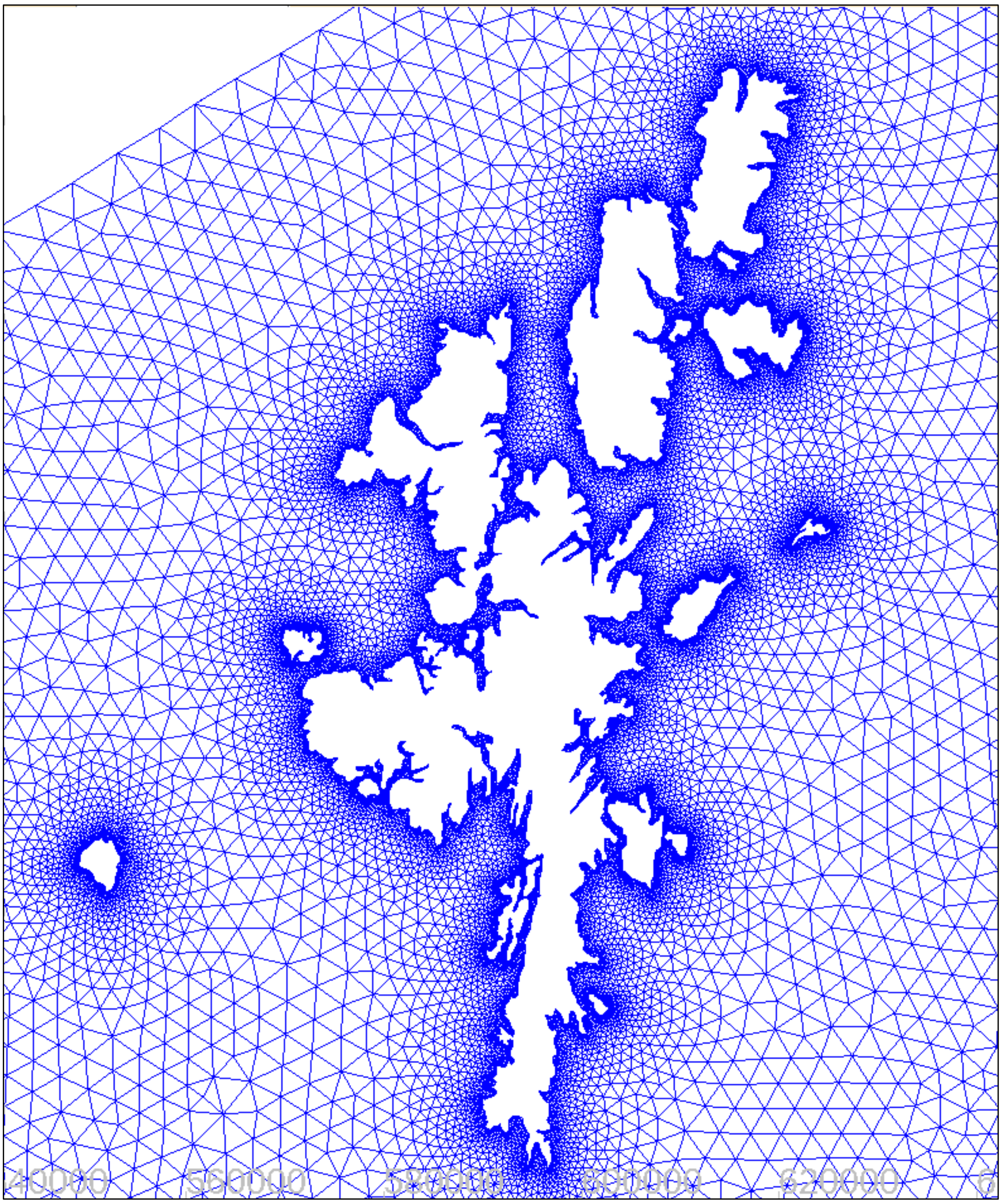

Figure 4 *Hydrodynamic mesh around Shetland.*

2.2 *Freshwater Inputs*

Figure 5 shows a map of freshwater discharge locations for the main rivers considered appropriate for the model. These were:

1. *Beauly-Ness system*
2. *Nairn*
3. *Findhorn*
4. *Spey*

5. *Deveron*
6. *Ugie*
7. *Hope*
8. *Kinloch*
9. *Naver*
10. *Halladale*
11. *Thurso*
12. *Wick*
13. *Helmsdale*
14. *Brora*
15. *Kyle of Sutherland*
16. *Conon*
17. *Orkney – Burn of Boardhouse*
18. *Orkney – Suso burn*

Average river flowrates were extracted from the G2G dataset [G2G, 2018] and a salinity value of 0 PSU and temperature of 8 ^{o}C was assumed. It should be noted that no freshwater discharge data were available for Shetland.

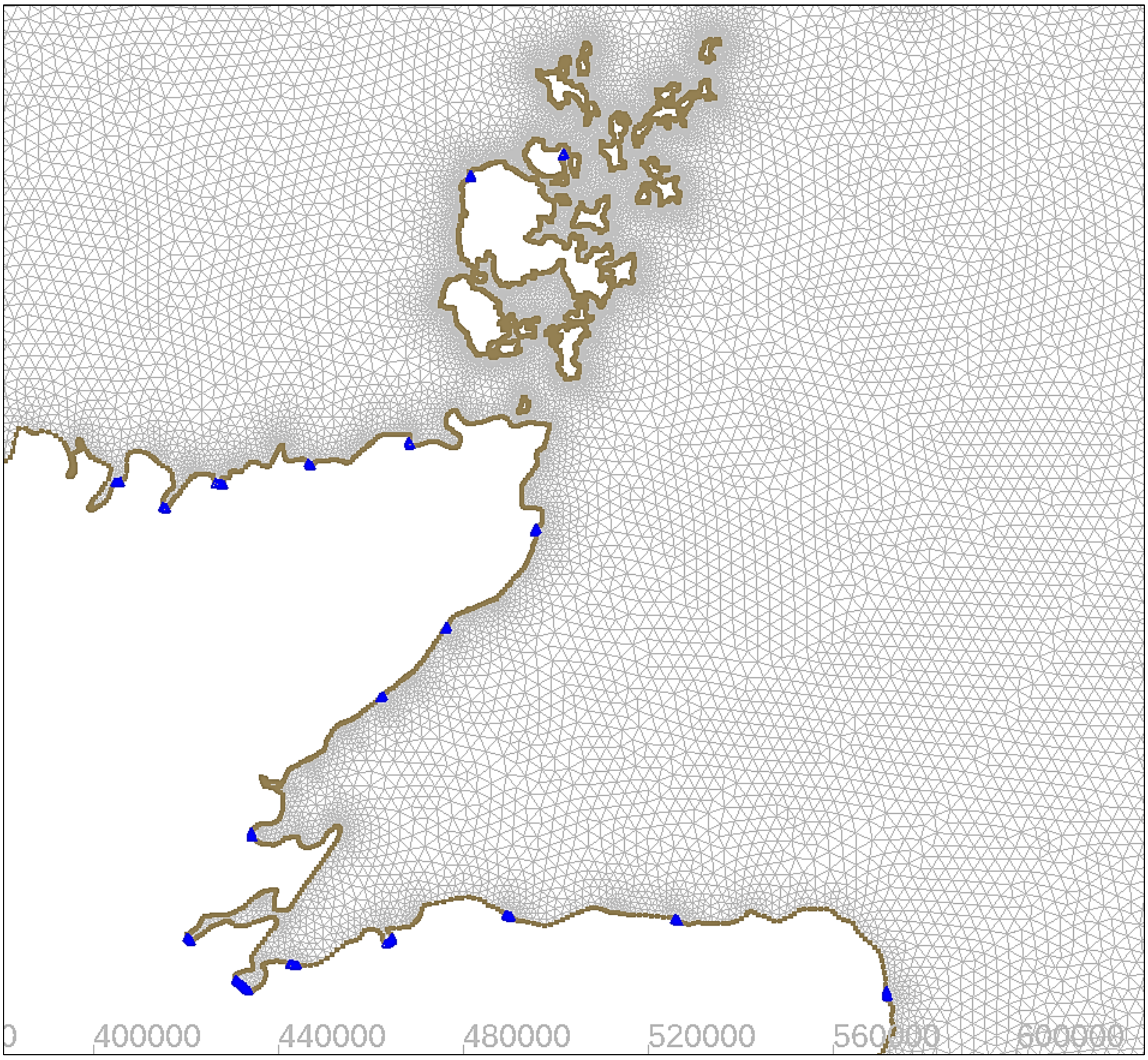

Figure 5 *River discharge locations shown in blue.*

2.3 *Bathymetry data*

Bathymetry data for the present study have been collected from two different sources: General Bathymetric Chart of the Oceans [GEBCO, 2023] and digitised Admiralty charts where required. The bathymetry used in the model is shown in Figure 6.

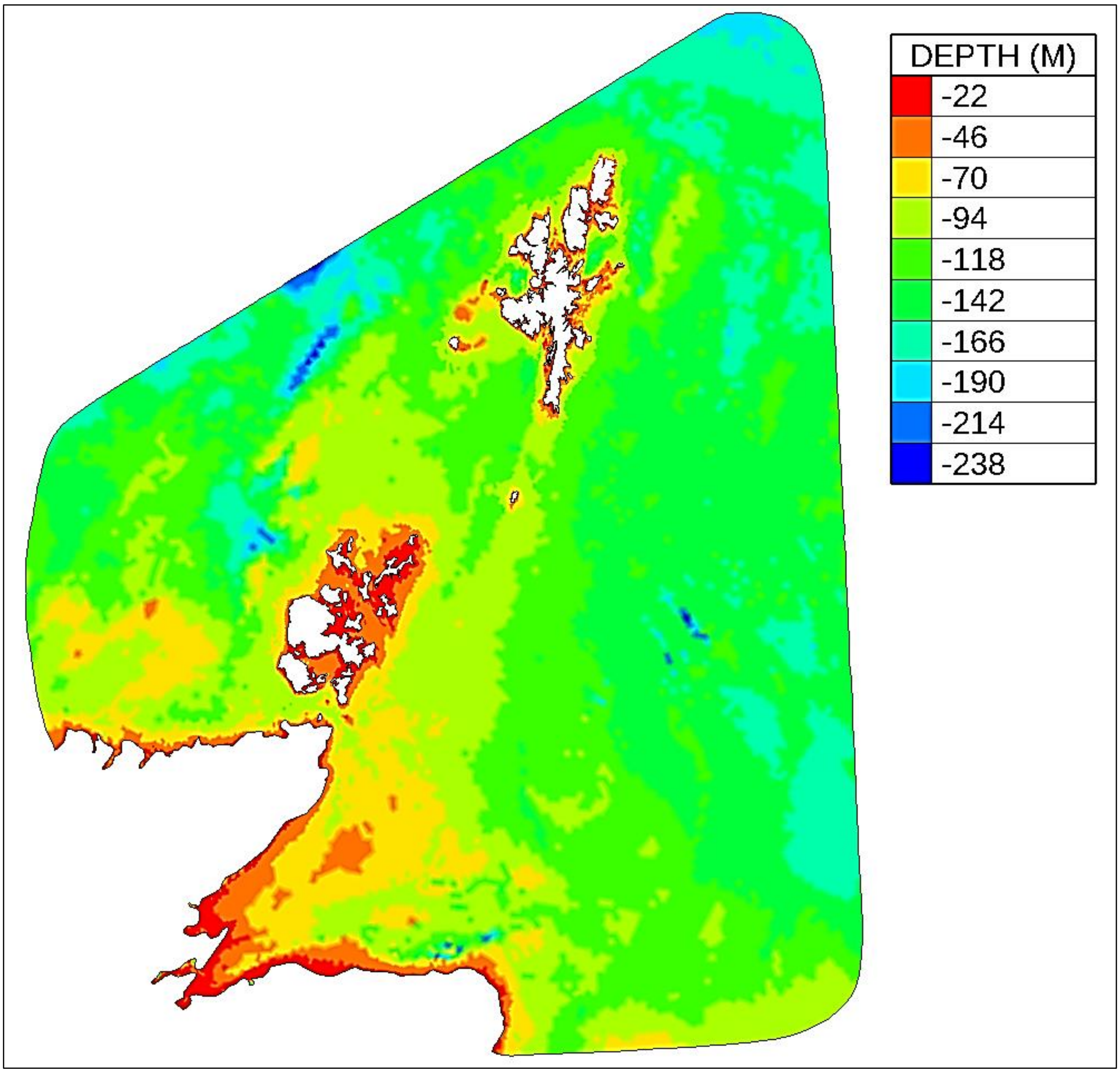

Figure 6 *Model bathymetry (m).*

For each simulation, the model was “spun-up” for 4 days 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.

Figures 7 and 8 show snapshots of the developed salinity and temperature fields, while Figures 9-12 highlight the general flow patterns around the Northern isles on flood and ebb tides.

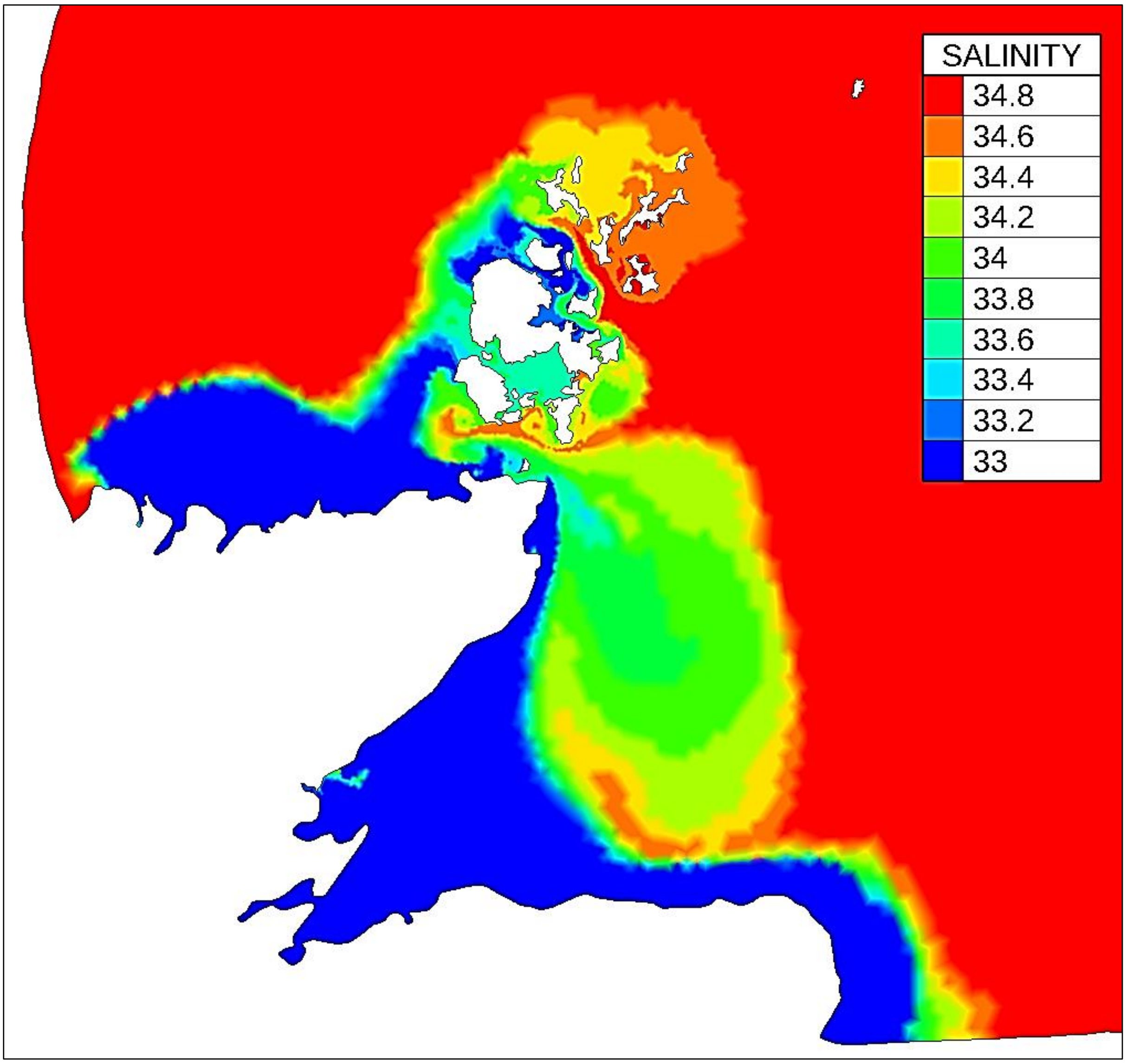

Figure 7 *Snapshot of surface salinity contours (PSU) on the 2nd July 2017 at 18h 20.*

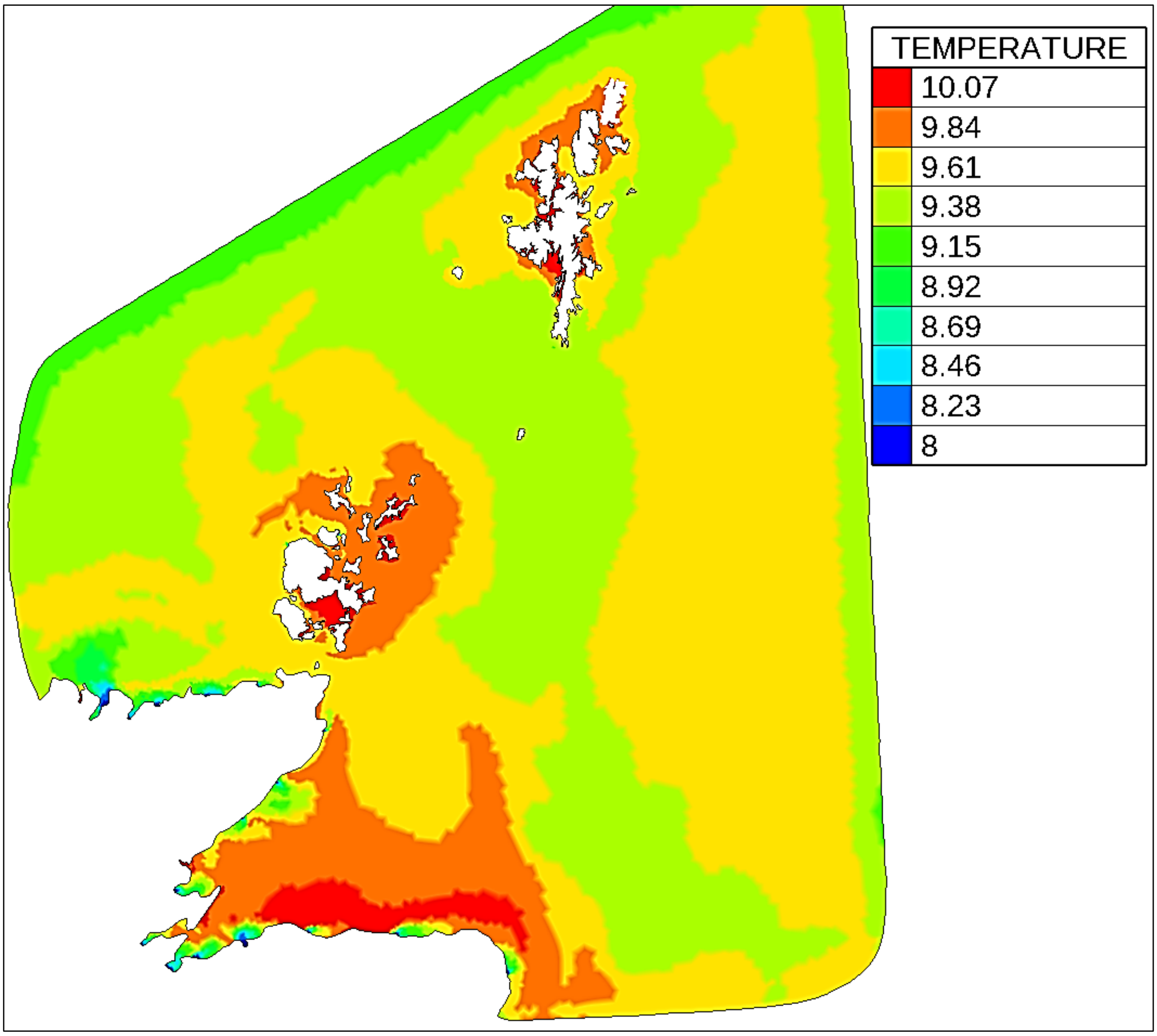

Figure 8 *Snapshot of surface temperature contours (^oC) on the 2nd July 2017 at 18h 20.*

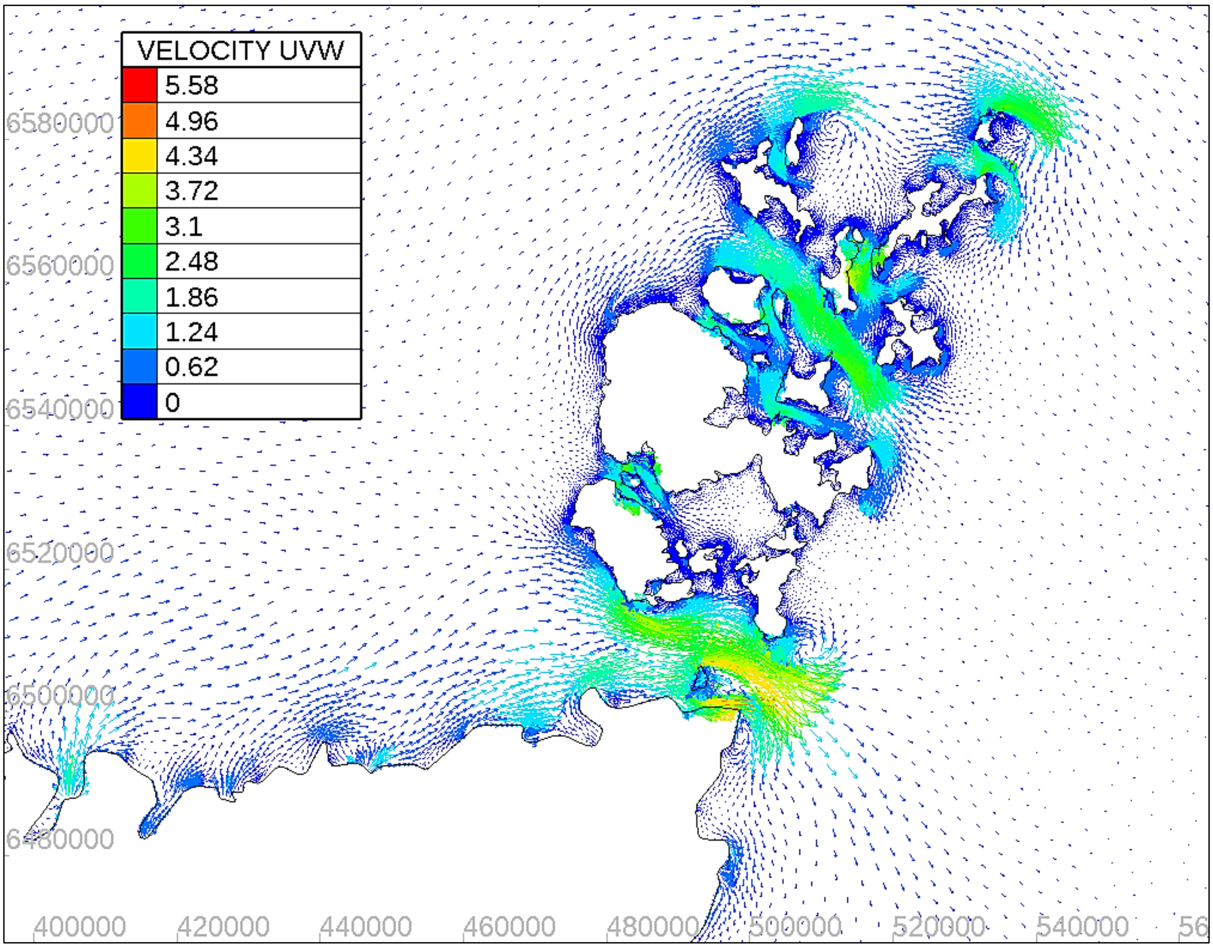

Figure 9 *General surface flow patterns (m/s) around Orkney on a flood tide.*

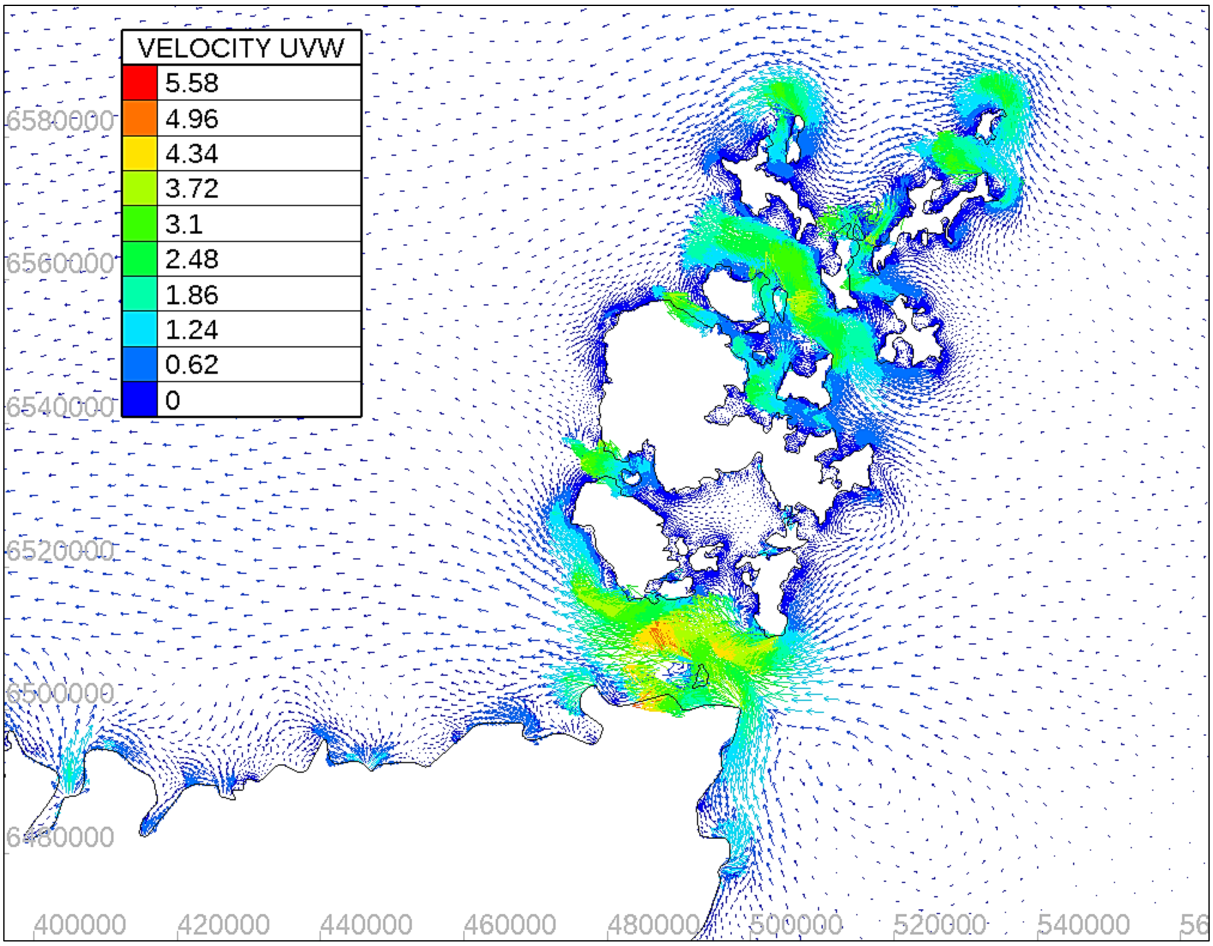

Figure 10 *General surface flow patterns (m/s) around Orkney on an ebb tide.*

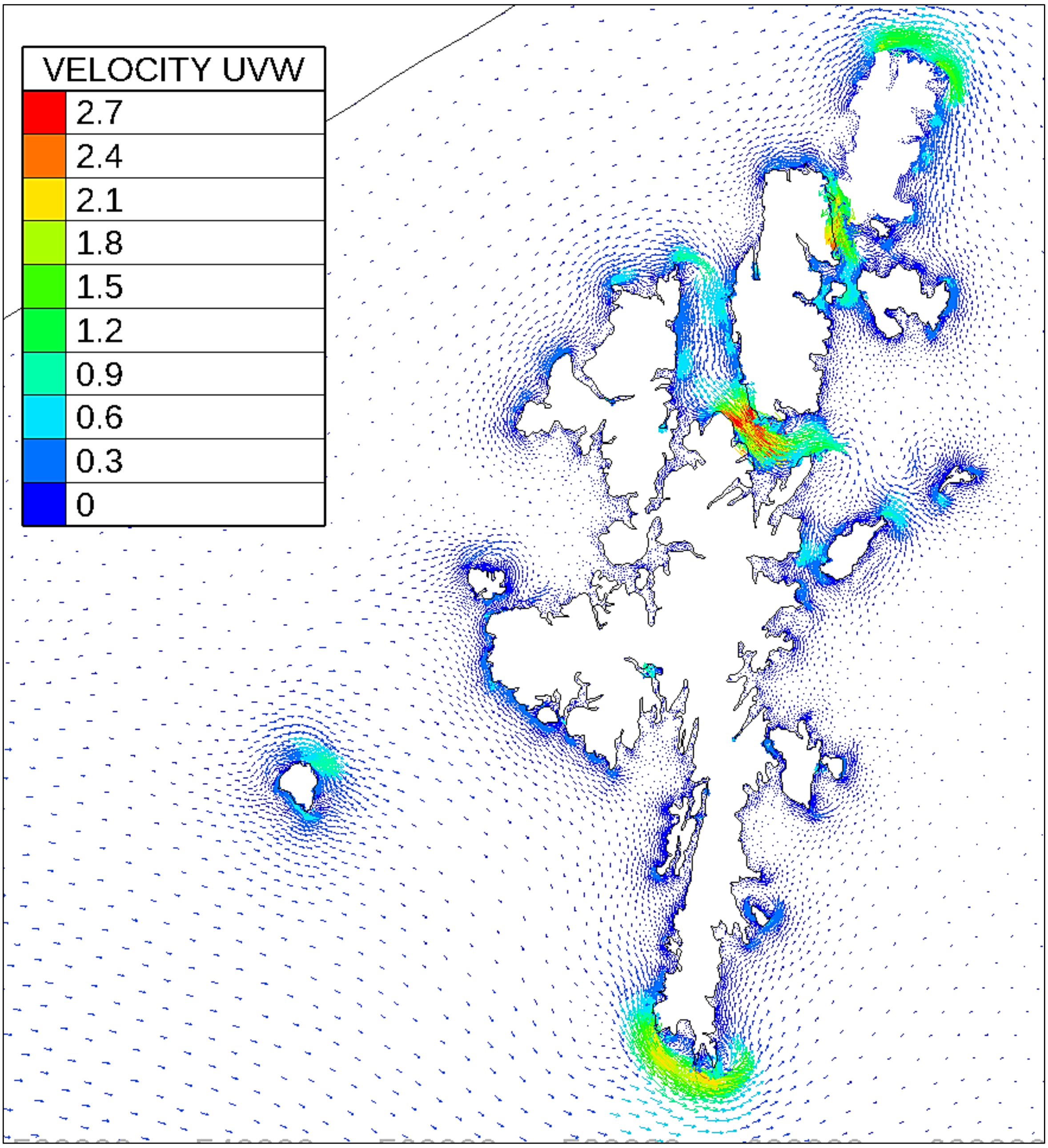

Figure 11 *General surface flow patterns (m/s) around Shetland on a flood tide.*

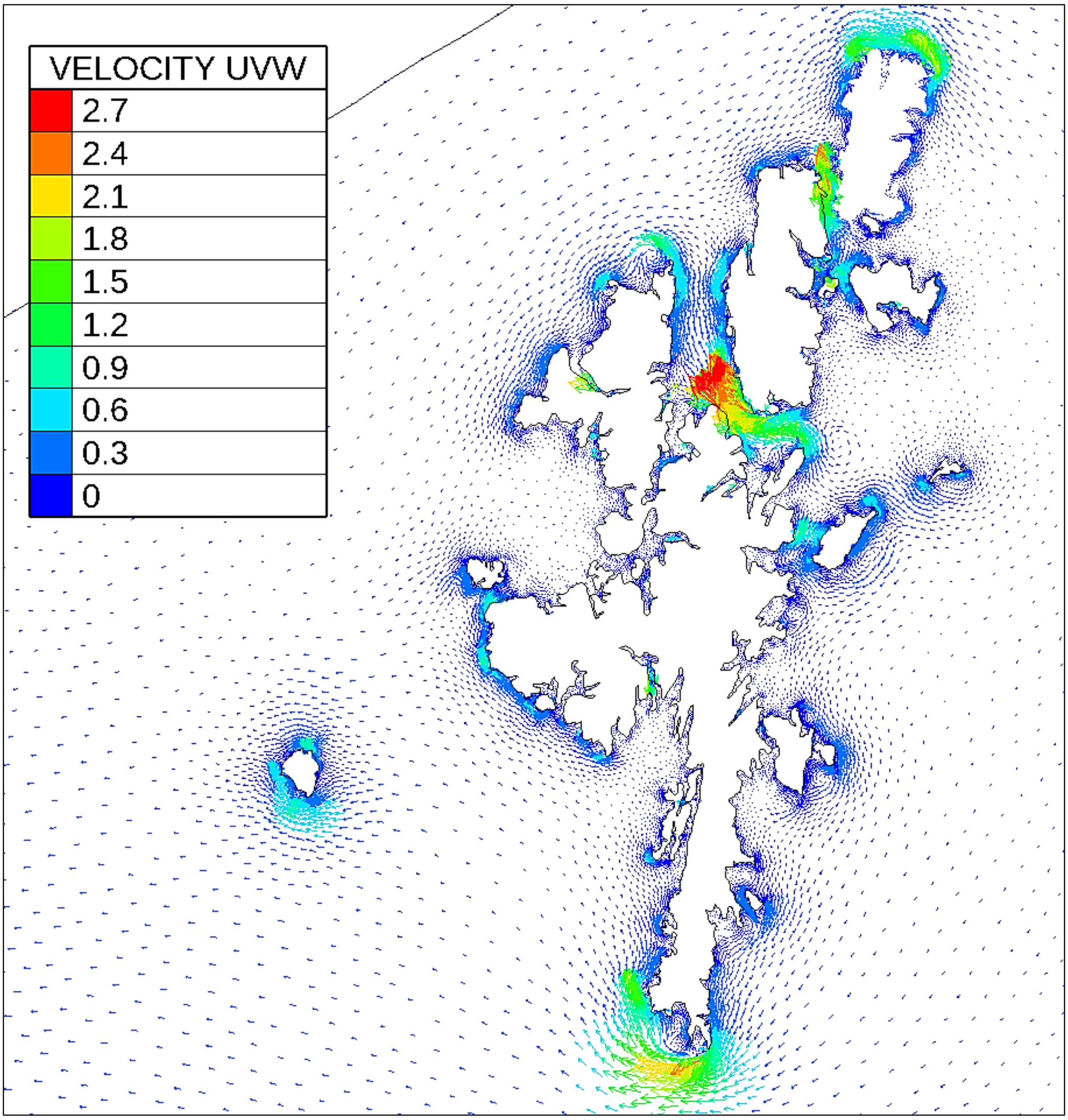

Figure 12 *General surface flow patterns (m/s) around Shetland on an ebb tide.*

2.4 Site Locations for Validation

For the validation study 2 sites were selected, one in Orkney and the other in Shetland, namely:

1. Mill Bay, Orkney.
2. Flaeshins, Shetland.

These were chosen on the basis of data availability and to provide a reasonable geographic spread across the model. Physical measurements of sea level, current speed and direction were provided at these locations by SEPA. Figures 13-16 show the locations of the measurement points and the Telemac model data is compared with the observed data from these points.

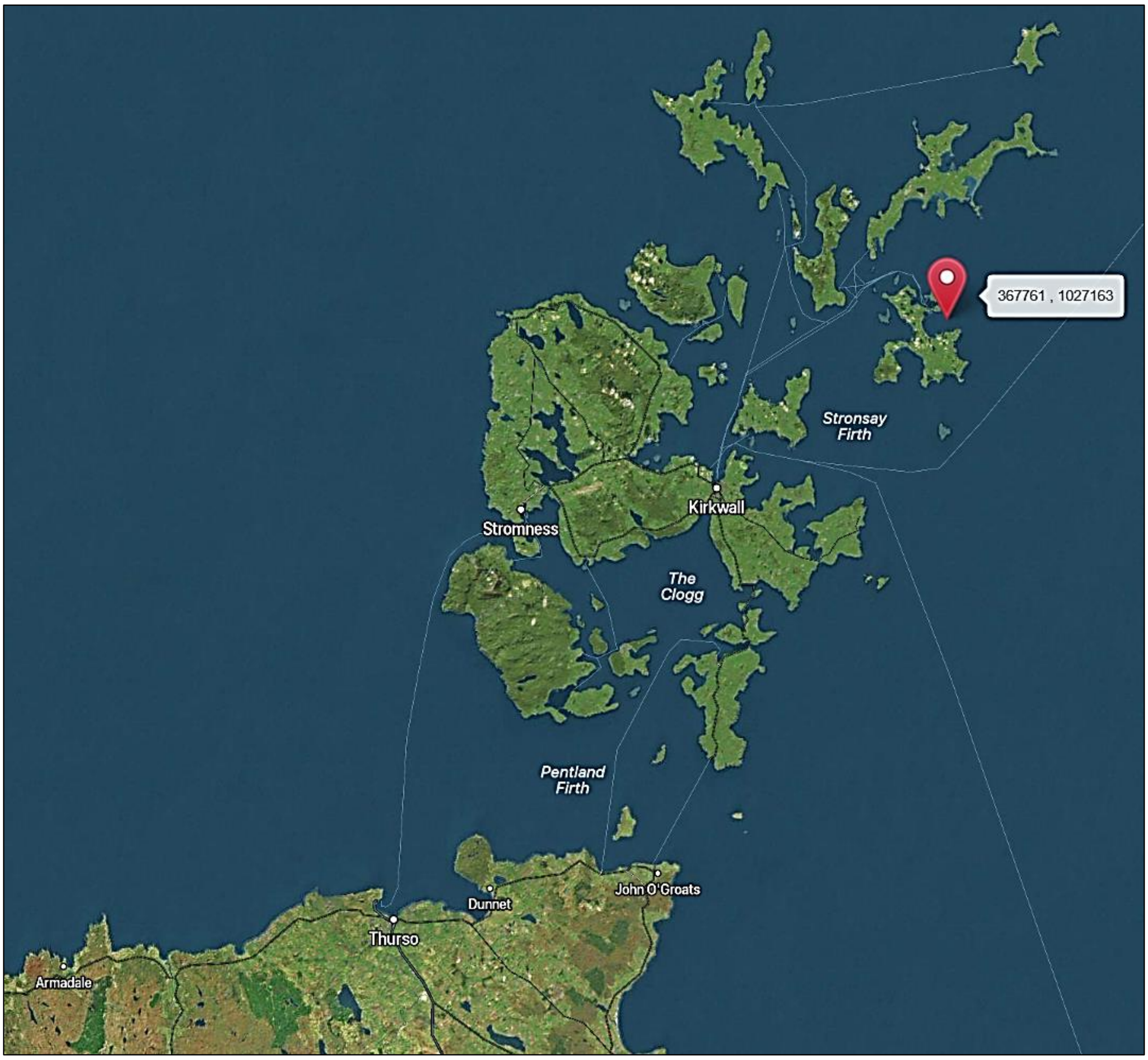

Figure 13 *Measurement point at Mill Bay, Orkney, 367761E and 1027163W.*

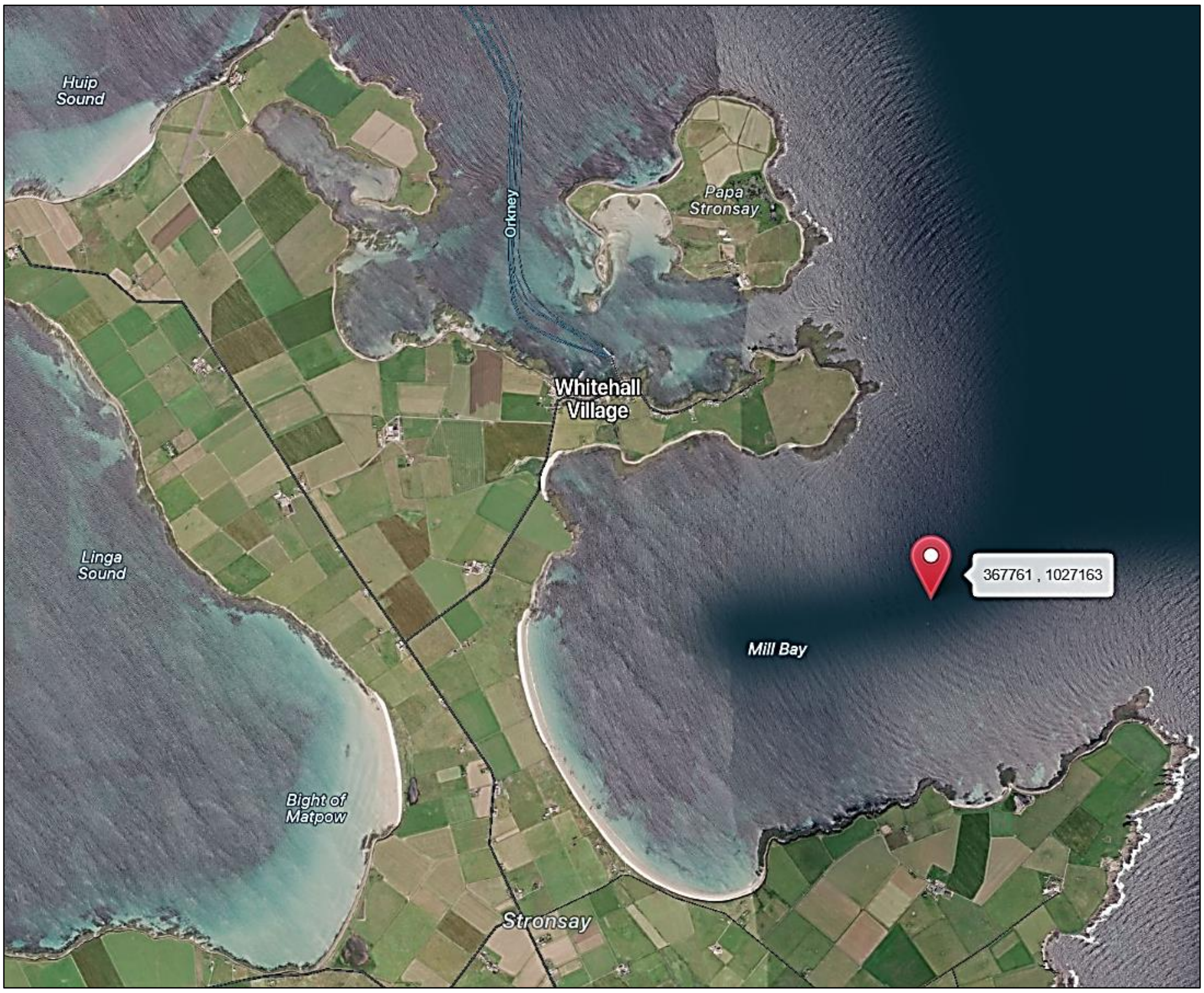

Figure 14 *Zoomed measurement point at Mill Bay, Orkney, 367761E and 1027163W.*

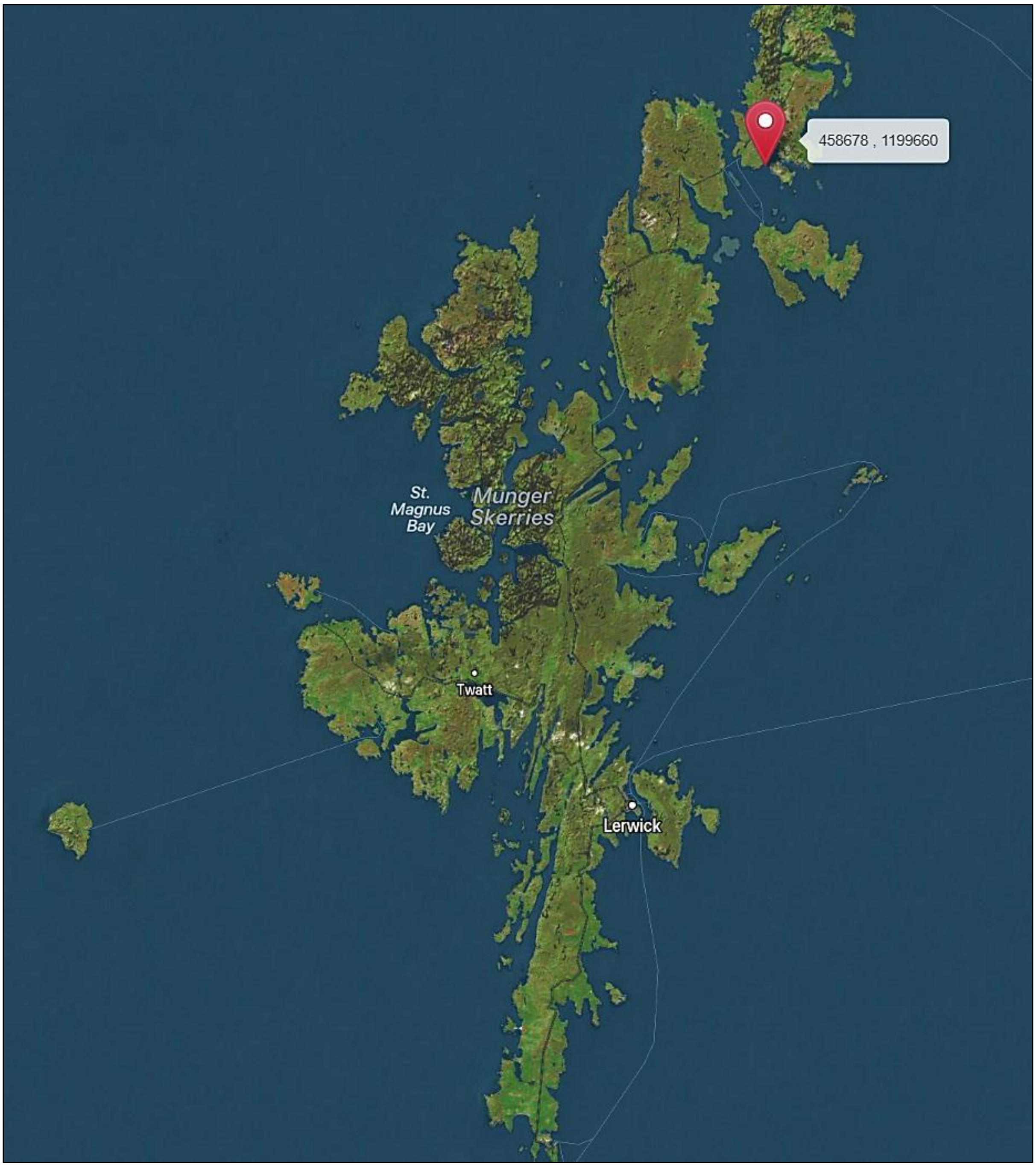

Figure 15 *Measurement point at Flaeshins, Shetland, 458678E and 1199660W.*

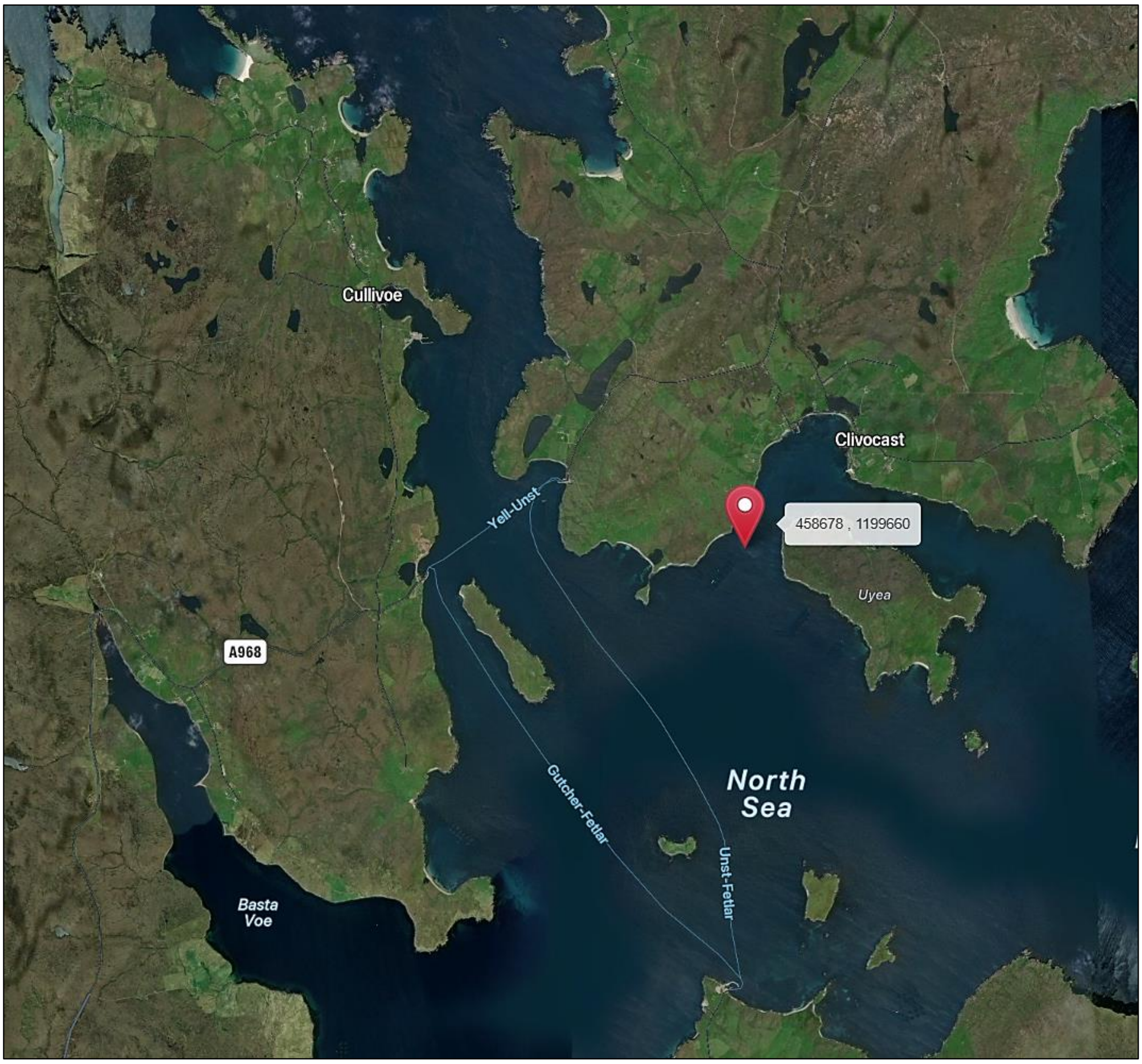

Figure 16 *Zoomed measurement point at Flaeshins, Shetland, 458678E and 1199660W.*

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 $0 \le d2 \le 1$, 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, 2024].

3.1 *Mill Bay, Orkney*

At the Mill Bay measurement location, corresponding to a depth near the farm cage bottom, the sea surface height was reasonably accurately modelled, with model skill score of 0.99 (Figure 17 and Table 1). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.11 m and 0.14 m respectively are about 3.5% and 4.5% of the spring tide range, respectively. 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 about 0.76 and 0.51, respectively. The values of the MAE and RMSE being in the range 3 – 5 cm s^{-1} (Table 1). Table 2 shows the comparison of modelled sea surface height, current speed and direction and timing of high water compared with the SEPA acceptable range [SEPA, 2019]. In general, the 3D model data are 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 18-22 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 measurement location at Mill Bay, Orkney from 11th- 26th June 2017.

	SSH	East	North
Skill, d2	0.99	0.51	0.76
Mean Absolute Error (MAE)	0.11 m	0.04 m/s	0.03 m/s
Root-Mean-Square Error (RMSE)	0.14 m	0.05 m/s	0.04 m/s

Table 2. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH), current speed, current direction (based on residual flow) and timing of high water at the measurement location at Mill Bay, Orkney from 11th- 26th June 2017.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	4.5 %	✓
SSH	+/- 15 % of Neap range (m)	11.7 %	✓
Current speed	+/- 0.1 Absolute - RMSE (m/s)	0.04	✓
Current speed	+/- 10 – 20 (%)	14.5	✓
Current direction	+/- 30 deg	20.7 deg	✓
Timing of high water / phase	+/- 15 mins	19 mins	×

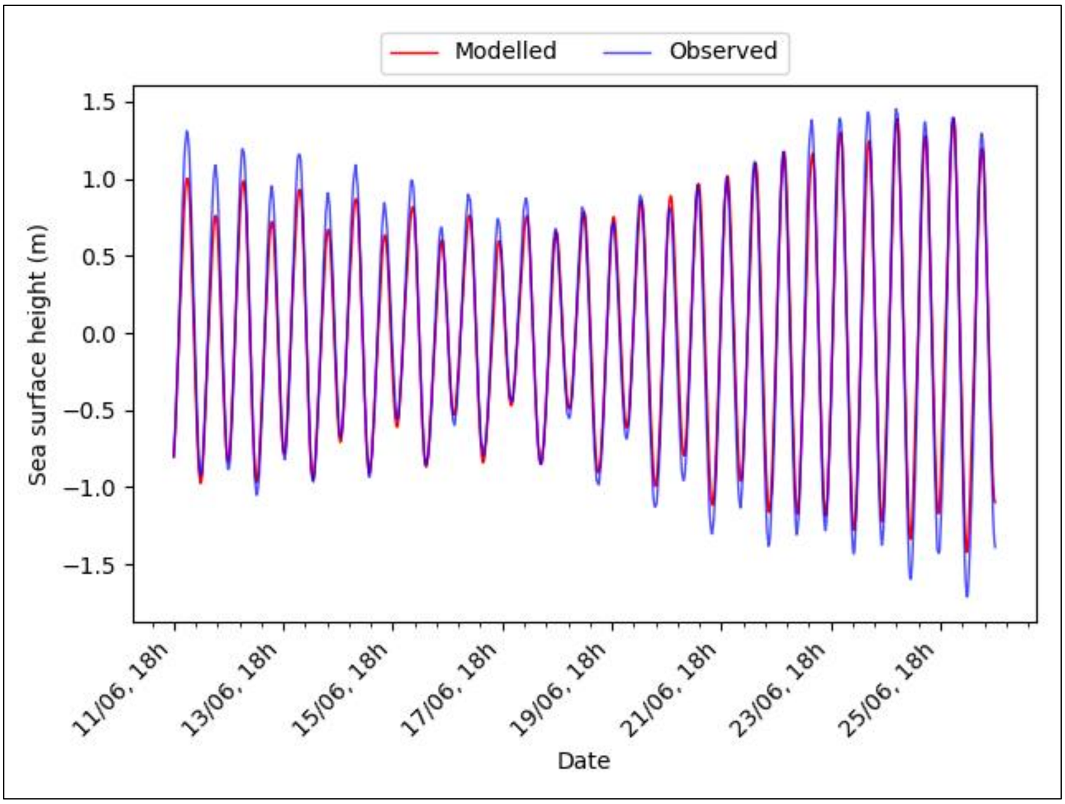

Figure 17 *Comparison between observed and modelled sea surface height from 11th- 26th June 2017 at Mill Bay, Orkney.*

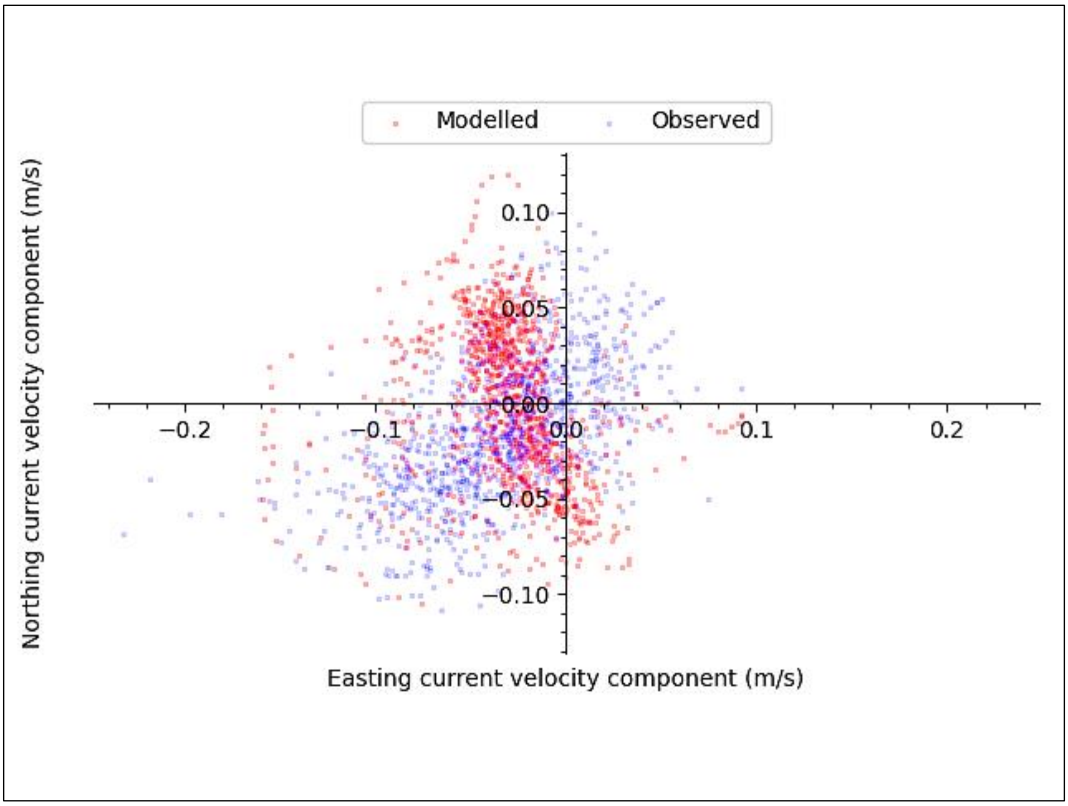

Figure 18 *Scatter plot of observed and modelled velocity from 11th- 26th June 2017 at Mill Bay, Orkney.*

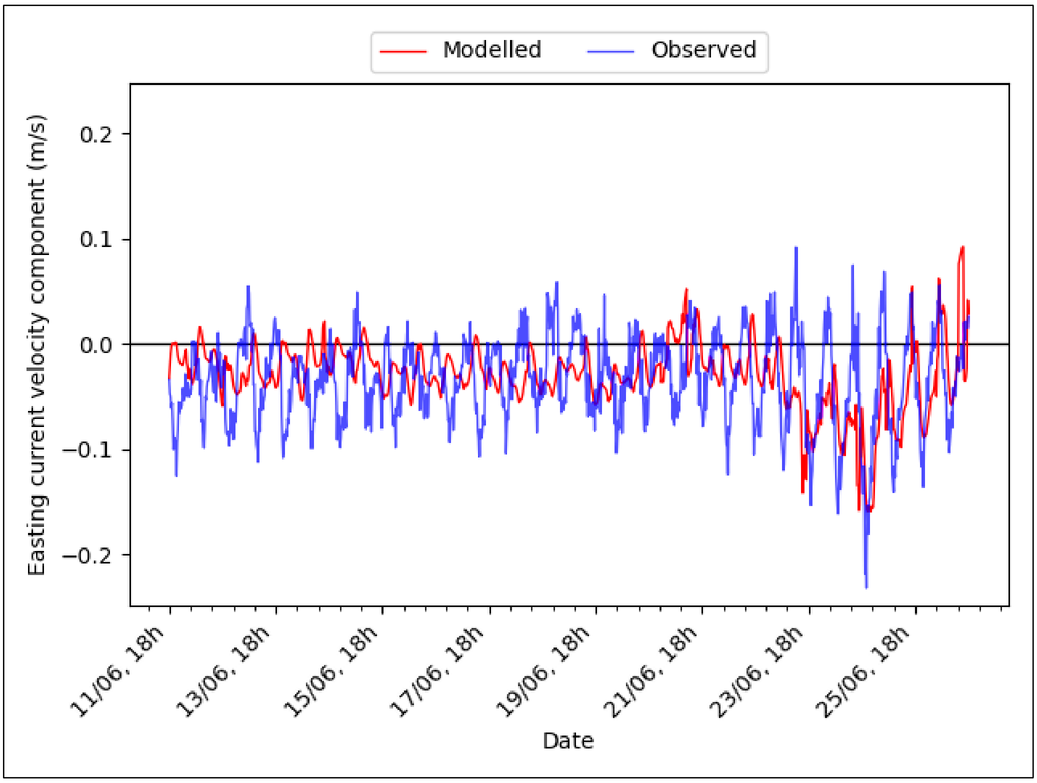

Figure 19 *Comparison between observed and modelled Easting velocity component from 11th- 26th June 2017 at Mill Bay, Orkney.*

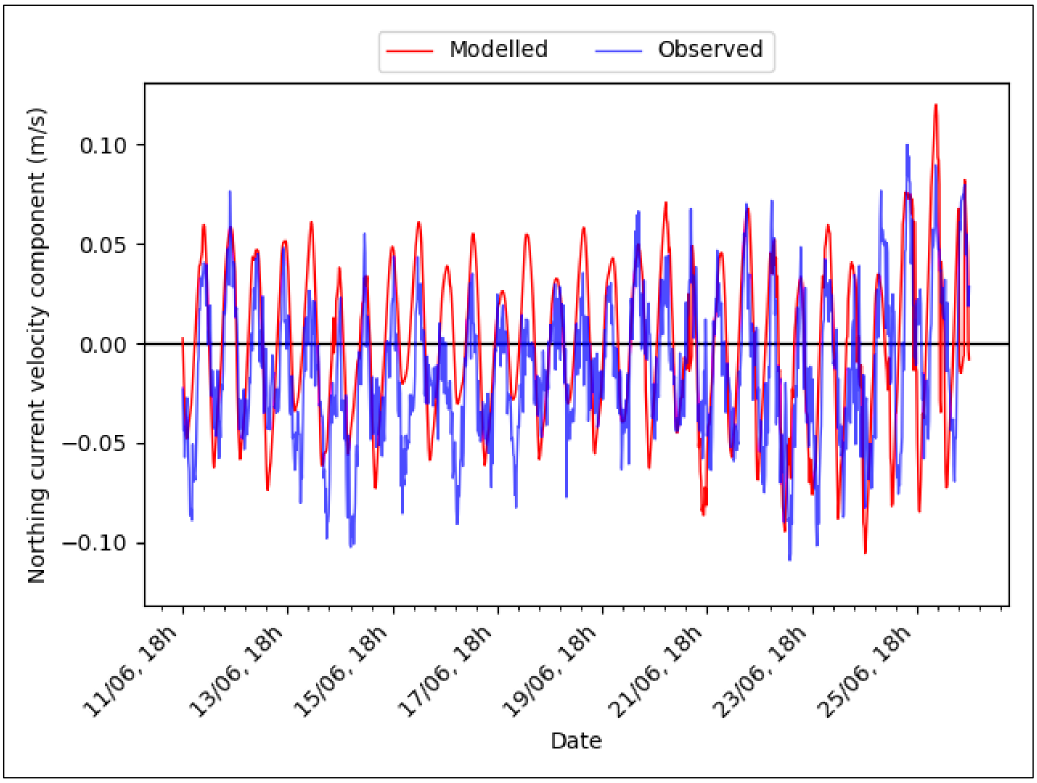

Figure 20 *Comparison between observed and modelled Northing velocity component from 11th- 26th June 2017 at Mill Bay, Orkney.*

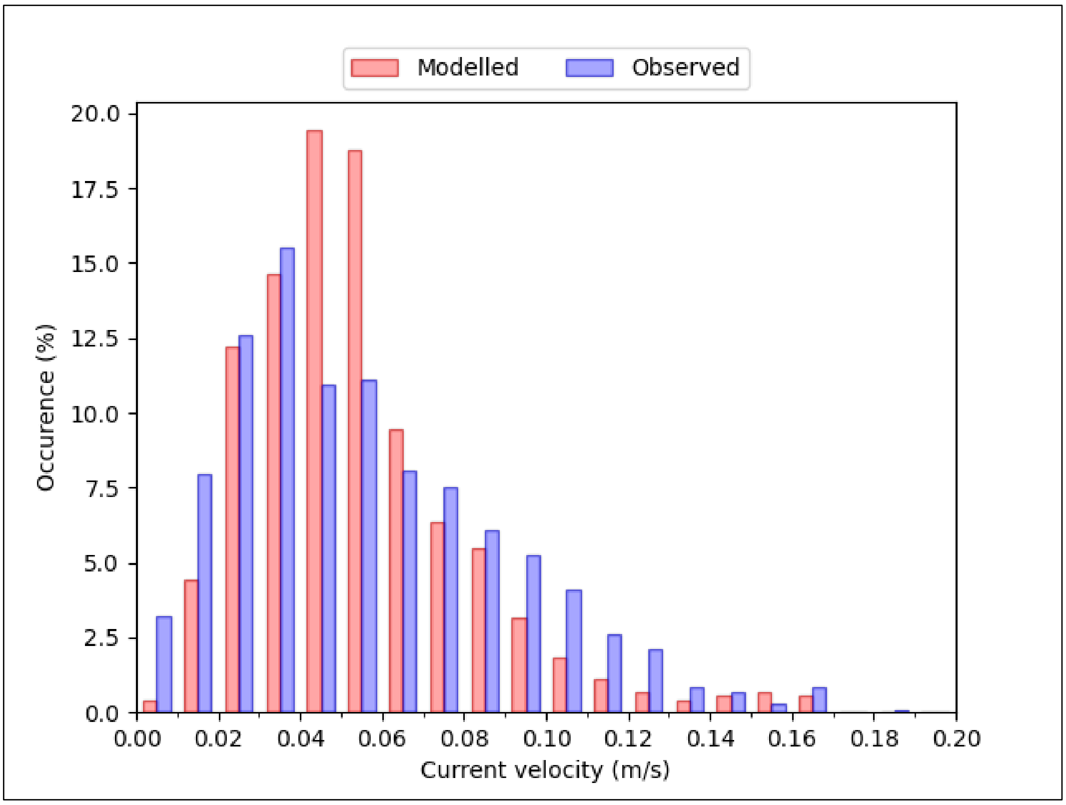

Figure 21 *Histogram of observed and modelled current speed component from 11th- 26th June 2017 at Mill Bay, Orkney. Model skill d2 = 0.93.*

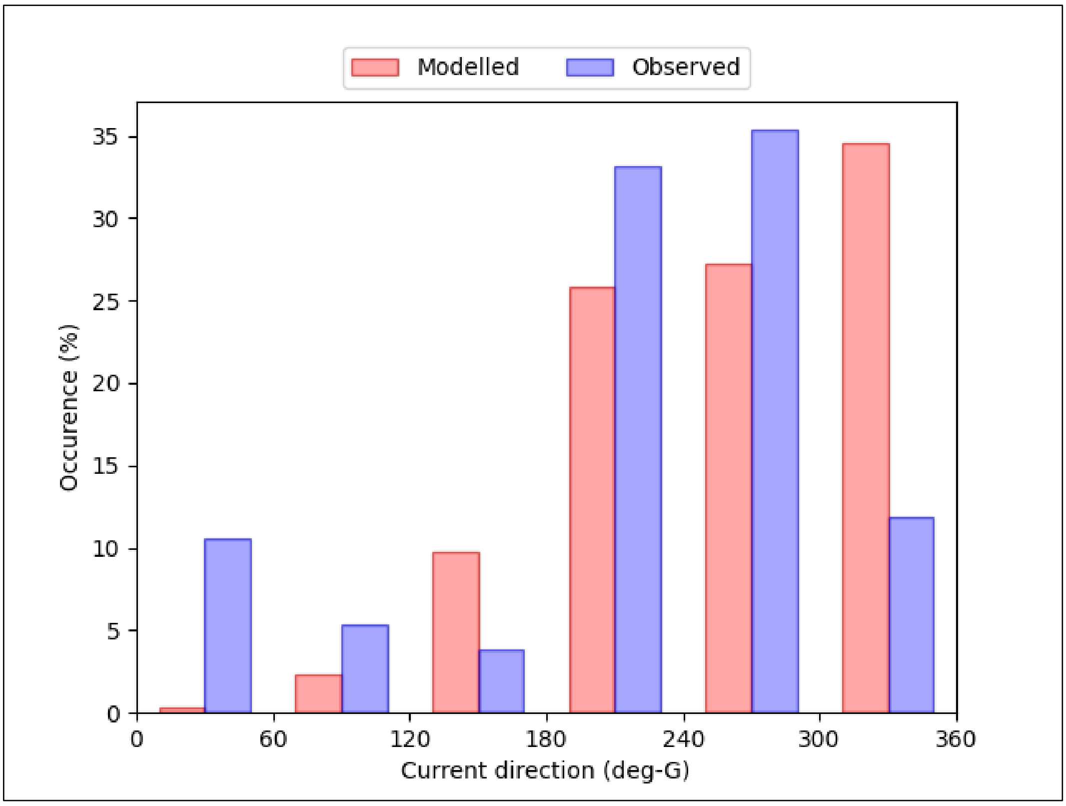

Figure 22 *Histogram of observed and modelled current direction from 11th- 26th June 2017 at Mill Bay, Orkney. Model skill d2 = 0.78.*

Further examples of Python script output are shown in Appendix A for the observed data at Mill Bay, Orkney.

3.2 *Flaeshins, Shetland*

At the Flaeshins measurement location, corresponding to a depth near the farm cage bottom, the sea surface height was reasonably accurately modelled, with model skill score of 0.99 (Figure 23 and Table 3). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.02 m is about 3.6% of the spring tide range. 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 about 0.46 and 0.33, respectively. The values of the MAE and RMSE being of the order of 3 cm s^{-1} (Table 3). Table 4 shows the comparison of modelled sea surface height, current speed and direction and timing of high water compared with the SEPA acceptable range [SEPA, 2019]. In general, the 3D model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 24-28 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 measurement location at Flaeshins, Shetland from the 23rd September - 8th October 2011.

	SSH	East	North
Skill, d2	0.99	0.33	0.46
Mean Absolute Error (MAE)	0.07 m	0.03 m/s	0.03 m/s
Root-Mean-Square Error (RMSE)	0.09 m	0.03 m/s	0.03 m/s

Table 4. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH), current speed, current direction (based on residual flow) and timing of high water at the measurement location at Flaeshins, Shetland from the 23rd September - 8th October 2011.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	3.6 %	✓
SSH	+/- 15 % of Neap range (m)	11.3 %	✓
Current speed	+/- 0.1 Absolute - RMSE (m/s)	0.02	✓
Current speed	+/- 10 – 20 (%)	19.5	✓
Current direction	+/- 30 deg	16 deg	✓
Timing of high water / phase	+/- 15 mins	11 mins	✓

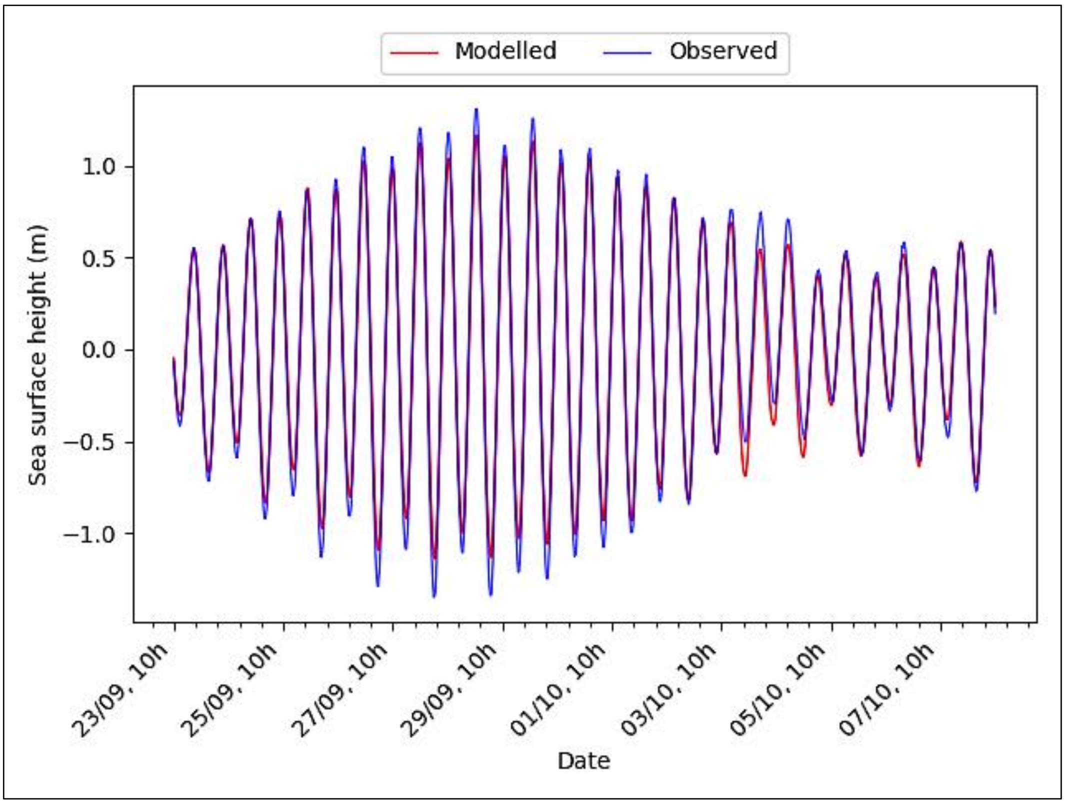

Figure 23 *Comparison between observed and modelled sea surface height from the 23rd September - 8th October 2011 at Flaeshins, Shetland.*

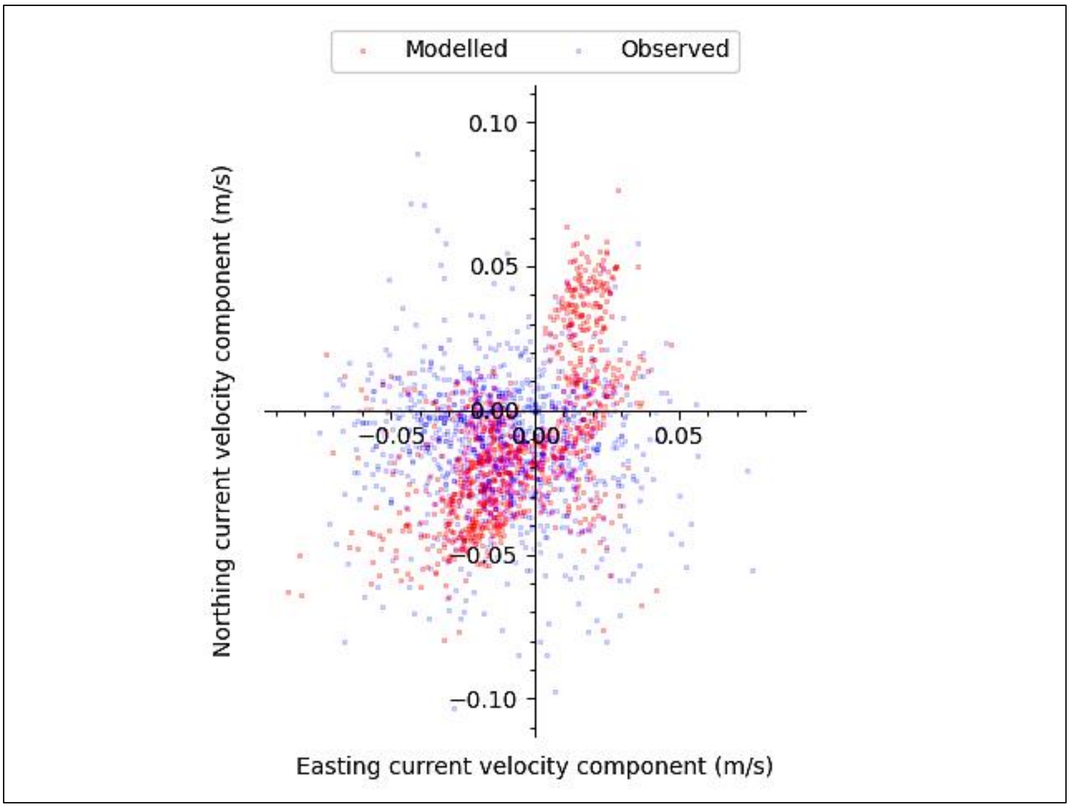

Figure 24 *Scatter plot of observed and modelled velocity from the 23rd September - 8th October 2011 at Flaeshins, Shetland.*

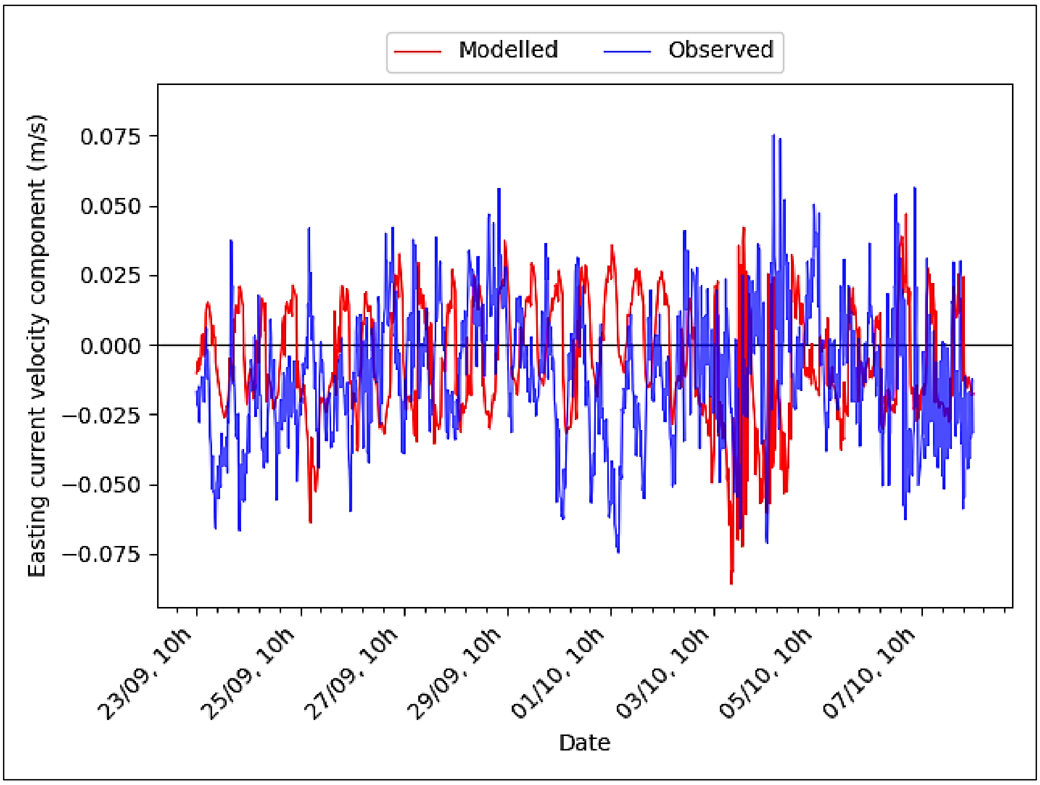

Figure 25 *Comparison between observed and modelled Easting velocity component from the 23rd September - 8th October 2011 at Flaeshins, Shetland.*

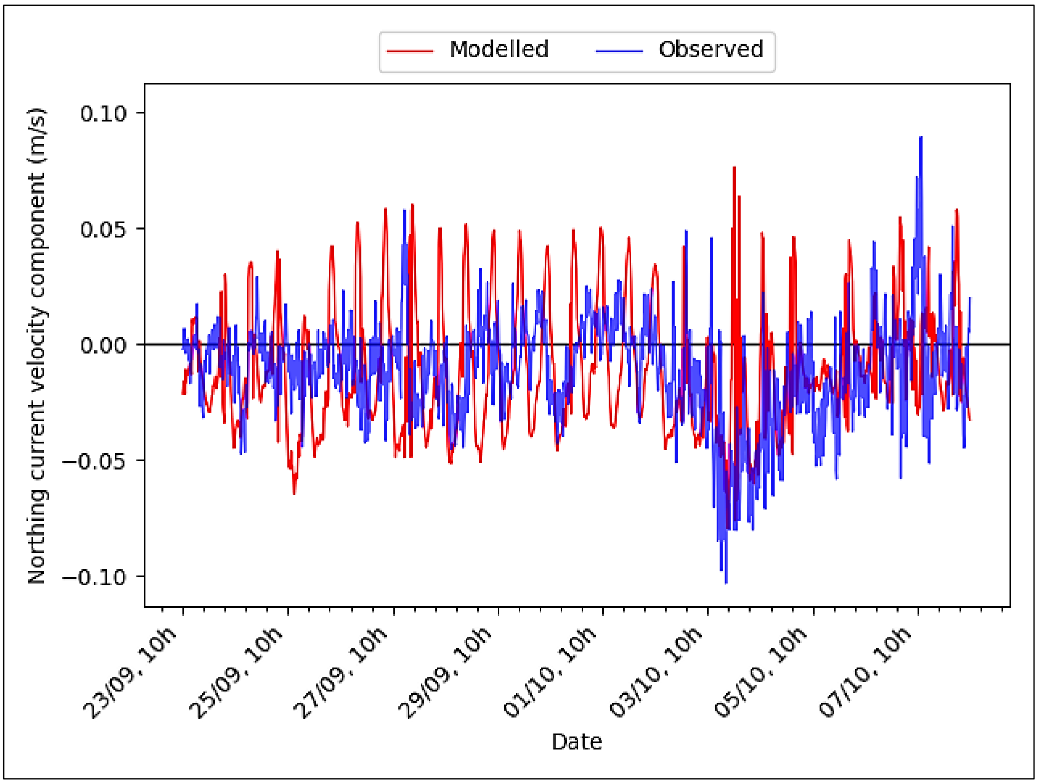

Figure 26 *Comparison between observed and modelled Northing velocity component from the 23rd September - 8th October 2011 at Flaeshins, Shetland.*

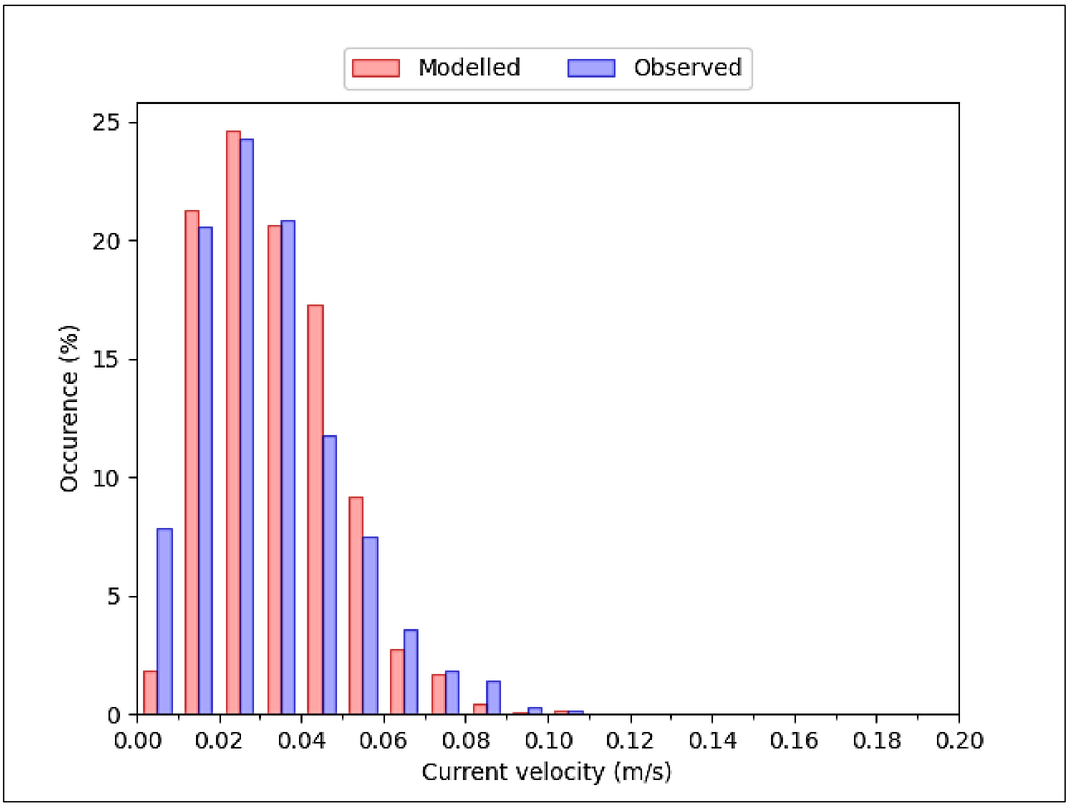

Figure 27 *Histogram of observed and modelled current speed component from the 23rd September - 8th October 2011 at Flaeshins, Shetland. Model skill d2 = 0.99.*

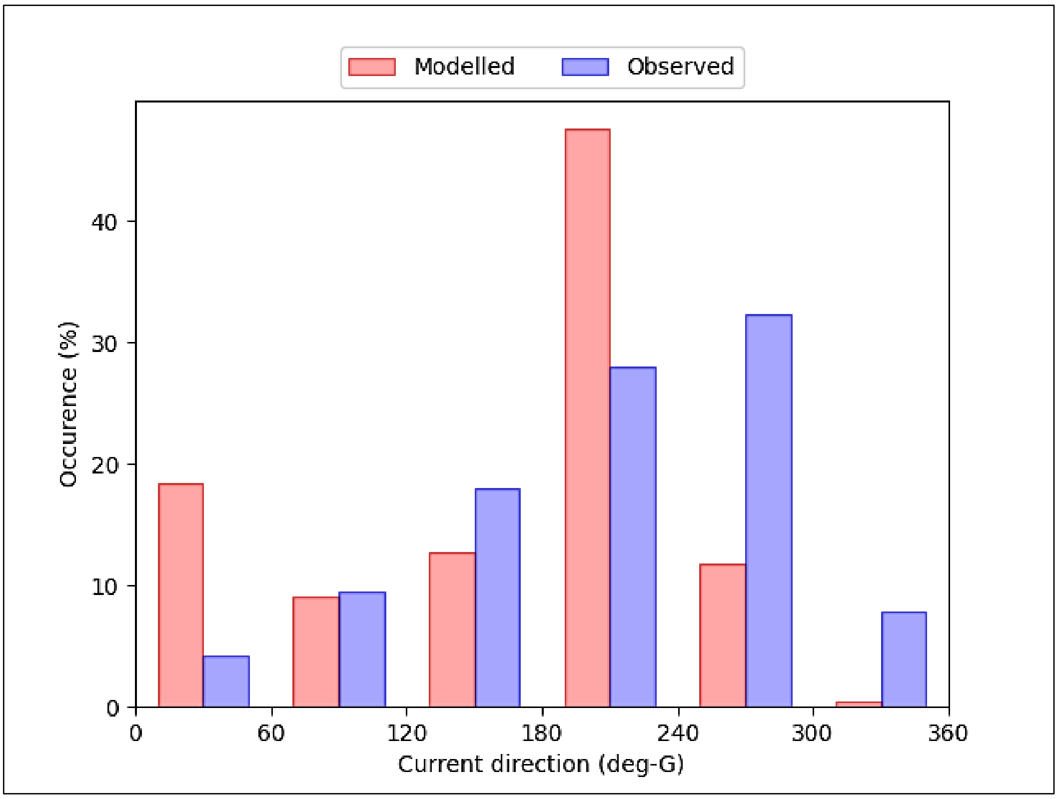

Figure 28 *Histogram of observed and modelled current direction from the 23rd September - 8th October 2011 at Flaeshins, Shetland. Model skill d2 = 0.67.*

4. 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 for Lice and Waste from Salmon Farms [CLAWS, 2024]. The hydrodynamic model, generated using the Telemac software, correctly simulates the propagation of the tide over the Northern isles and the 3D approach provides a reasonable description of the sea level and flow currents in the area. In general, the model data compares favourably against the SEPA calibration/validation requirements for hydrodynamic and discharge modelling [SEPA, 2019] at locations across the model domain. It may be concluded that the model provides general insight into spatial and temporal variations in the flow environment around Orkney, Shetland, and the North East coast of Scotland. It offers a suitable basis for modelling sea lice impact on wild salmon and sea trout, as well as assessing near-field and far-field dispersion effects of lice treatment pesticides, feed waste, and dissolved nutrients.

References

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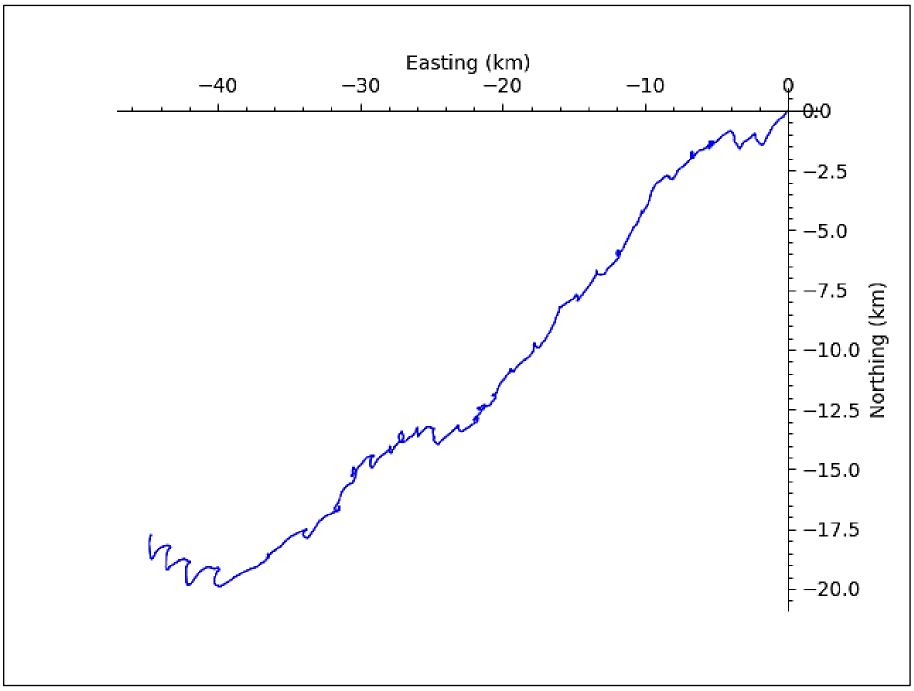
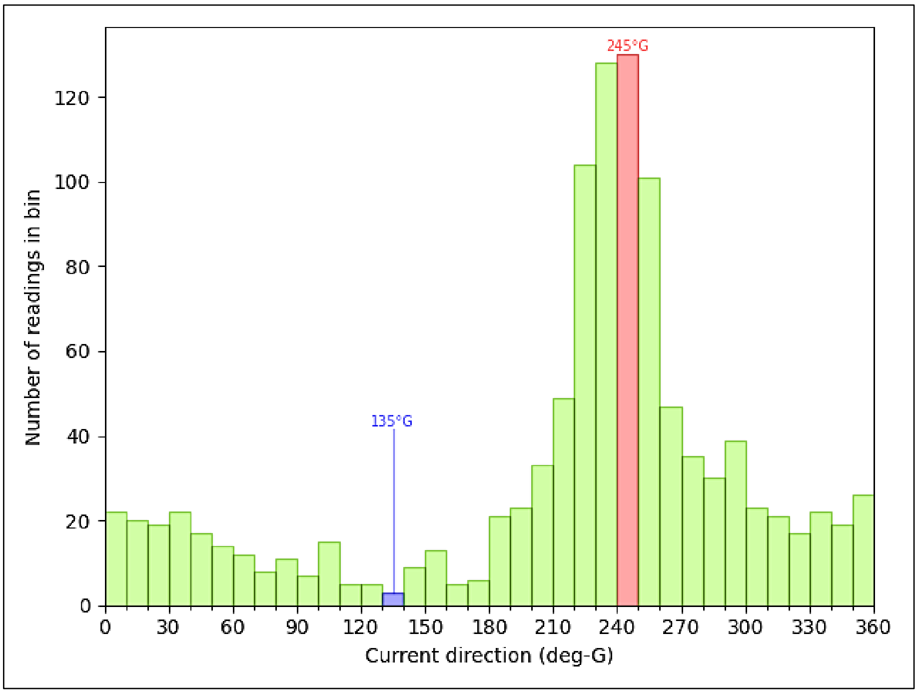
APPENDIX A

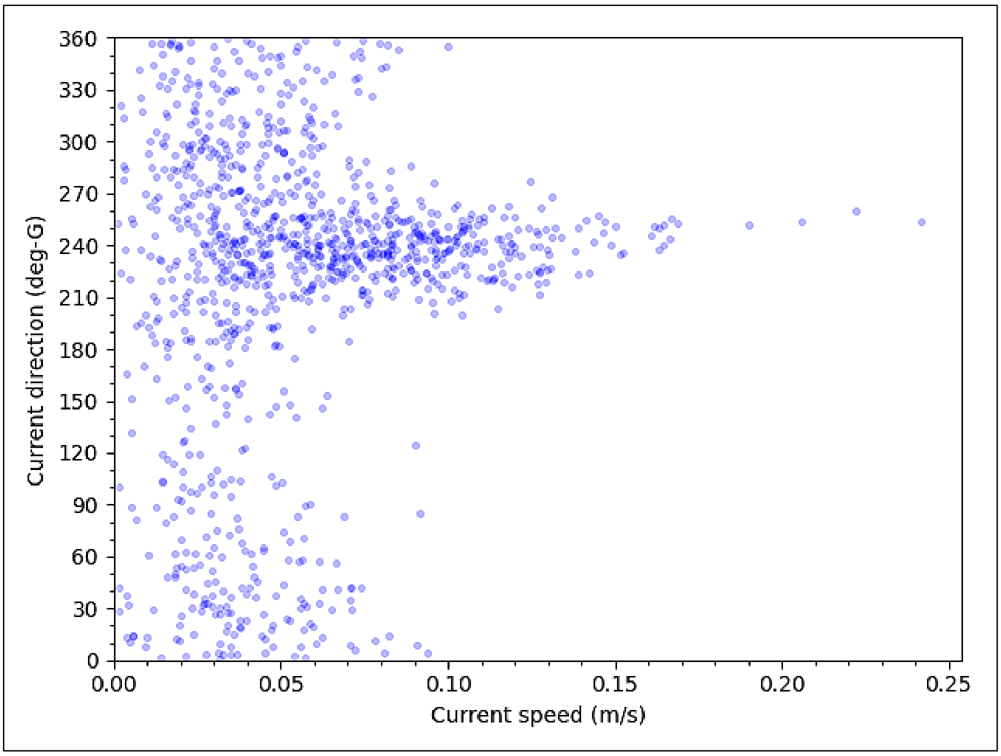
Examples of additional plots created using the post-processing Python scripts in CLAWS for the observed data at Mill Bay, Orkney are shown below:



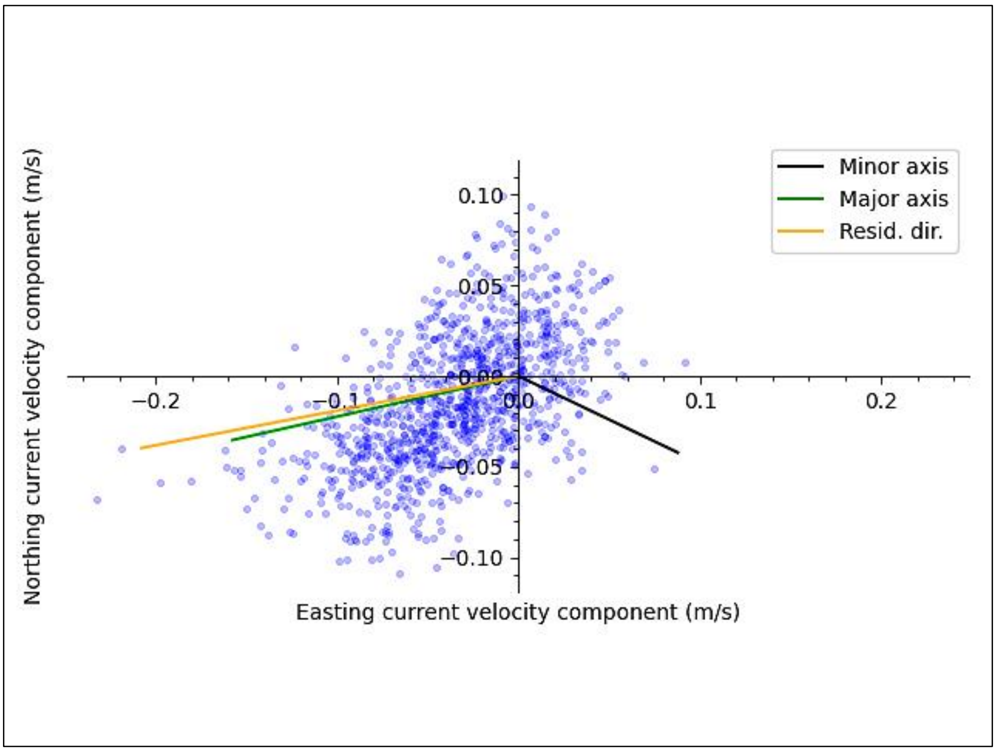
A.1 Cumulative vector



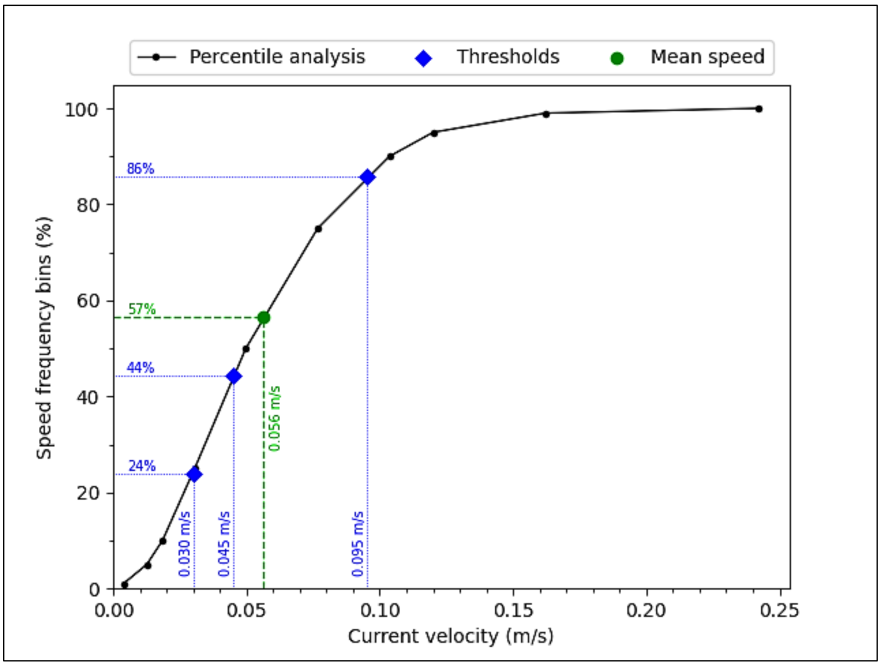
A.2 Flow direction bar graph



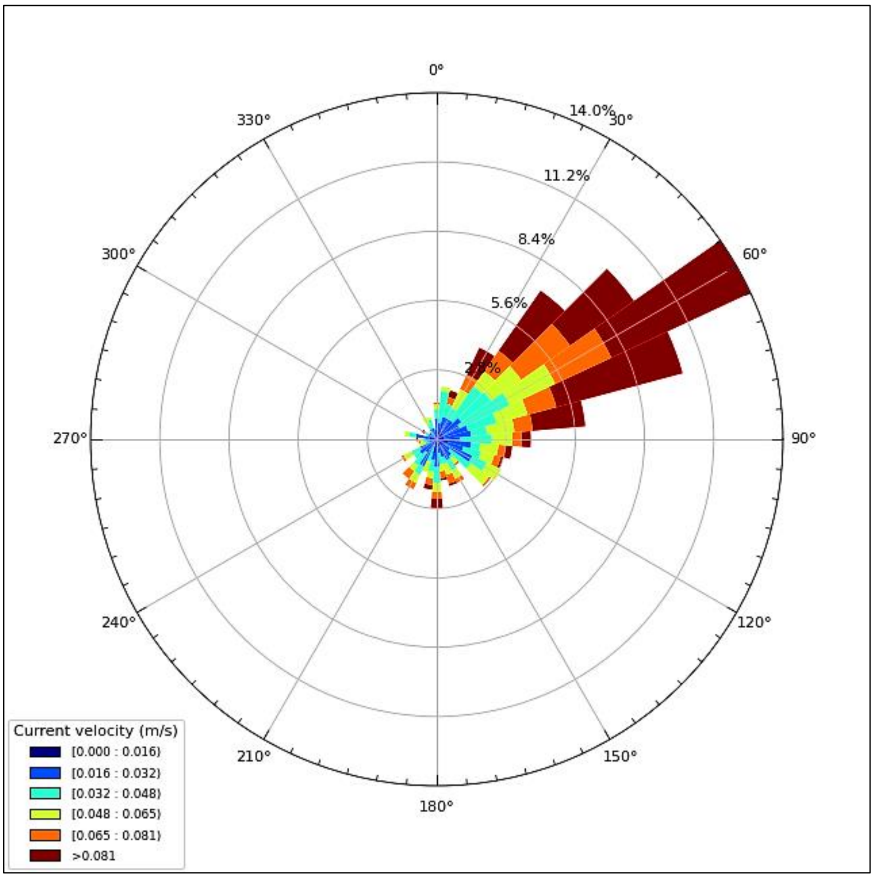
A.3 Direction vs current speed



A.4 Easting vs Northing velocity



A.5 Speed percentiles



A.6 Ocean Current rose