CLAWS – Chemicals Lice and Waste from Salmon Farms

1. Hydrodynamics Model

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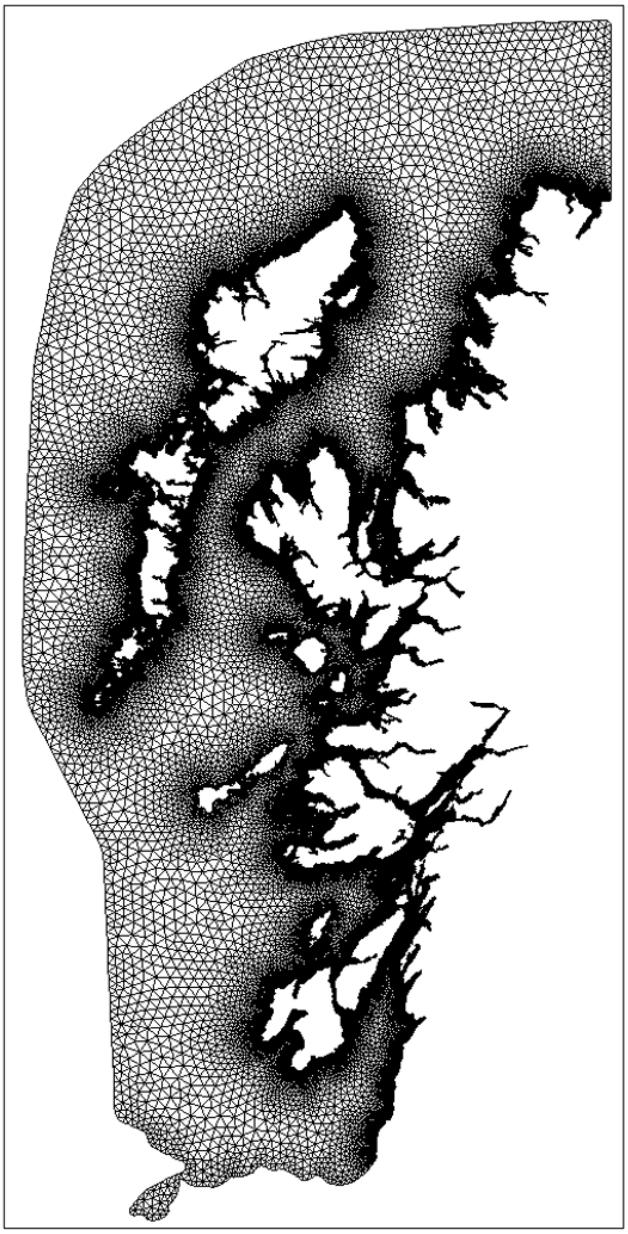

Executive Summary

Two- and three-dimensional hydrodynamic (HD) models of the West Coast of Scotland have been constructed using the Telemac code [TELEMAC, 2022]. The 3D model domain extends from the Mull of Kintyre in the South to Cape Wrath in the North and includes all main islands of the West Coast. The 2D model is a smaller subset of the larger 3D case. Initial model validation has been reported elsewhere [SCANLON, 2022] and this report focuses on further validation of the models against physical observations in Loch Hourn.

The oceanography of the West Coast is 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 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. In the 2D case, sea-bed friction was varied in order to calibrate the model.

The models were validated against published observed hydrographic data (water levels and currents) with a specific focus on Loch Hourn. These data were lifted from tide gauges and current surveys performed by the salmon farm operator Mowi.

The models correctly simulate the propagation of the tide over the West Coast and both 2D and 3D approaches provide a reasonable description of the flow currents within Loch Hourn 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, 2022]. Other modules in the CLAWS toolbox include those for pesticide treatments, dissolved nutrients and solid particle feed waste.

With this report and other validation studies [SCANLON, 2022] it is concluded that the Telemac hydrodynamic models can capture the general dynamics of the water levels and current circulation around the West Coast of Scotland with a specific focus in this report on validation in Loch Hourn.

The models offer general insight into the spatial and temporal variation in the flow environment around the West Coast of Scotland. They also provide a suitable basis for modelling sea lice impact on wild salmon and sea trout and an assessment of both the near-field and far-field dispersion effects of lice treatment pesticides, feed 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 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 Vincent Casseau *MSc PhD, Engineering Consultant*

Vincent is an engineering consultant with background experience in fluid dynamics and computer science. He obtained his Masters engineering degree in Aeronautics and Aerospace at ISAE-ENSMA, Poitiers, France. Following an internship at the European Space Agency, Vincent undertook a Ph.D in high-speed re-entry physics at the University of Strathclyde under the supervision of Dr Tom Scanlon, where he developed an open-source platform to solve hypersonic continuum and rarefied flows that has since been used in 15+ countries. Vincent was a Postdoctoral Fellow at McGill University in Montreal, Canada from 2019-2021, where he co-led the development of a monolithic software system to simulate hypervelocity civilian craft, partnering with Ansys and Lockheed Martin.

1 Introduction and Motivation

This report has been prepared for the Friends of the Sound of Jura, 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 of 2D and 3D hydrodynamics models to capture adequately the current patterns around Scotland's West coast and islands.

A 2D and 3D hydrodynamics approach based on the Telemac code [TELEMAC, 2022] has been employed. The hydrodynamic models contain the influence of weather forcing and, in the case of 3D, 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, Lice and Waste from Salmon Farms [CLAWS, 2022]. Other modules in the CLAWS software suite include those for pesticide treatments, dissolved nutrients and solid particle feed waste.

2 Background Data

2.1 *Site location*

The focus of the validation process is at the Mowi salmon farm Creag an t'Sagairt in Loch Hourn. Figures 1 and 2 show the location of the farm while Figure 3 shows the position of the sea level and water current measurement devices. The Telemac model data is compared with the observed data from the measurement meters with IDs 246, 253 and 254.

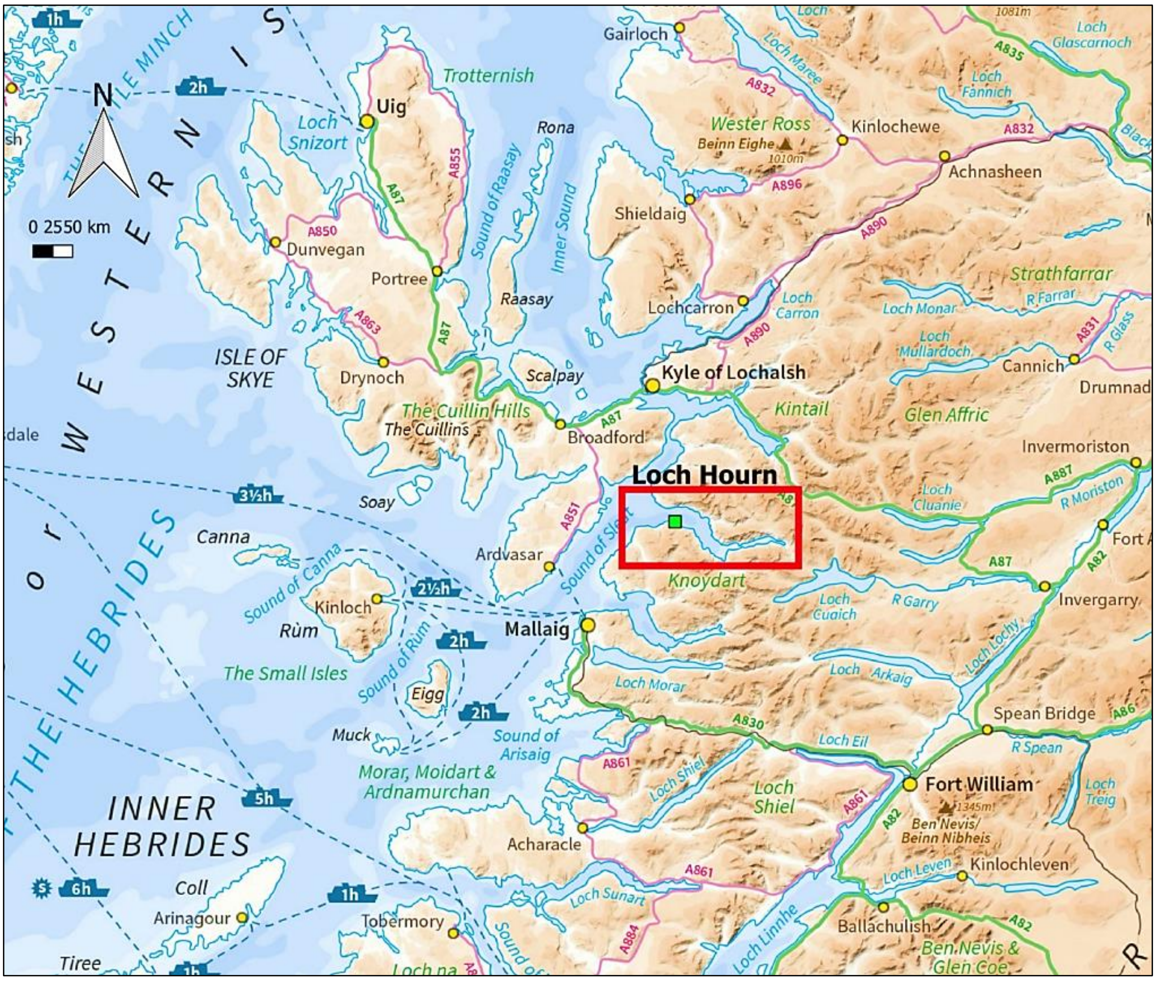


Figure 1 *Loch Hourn and location of Mowi's Creag an t'Sagairt salmon farm.*

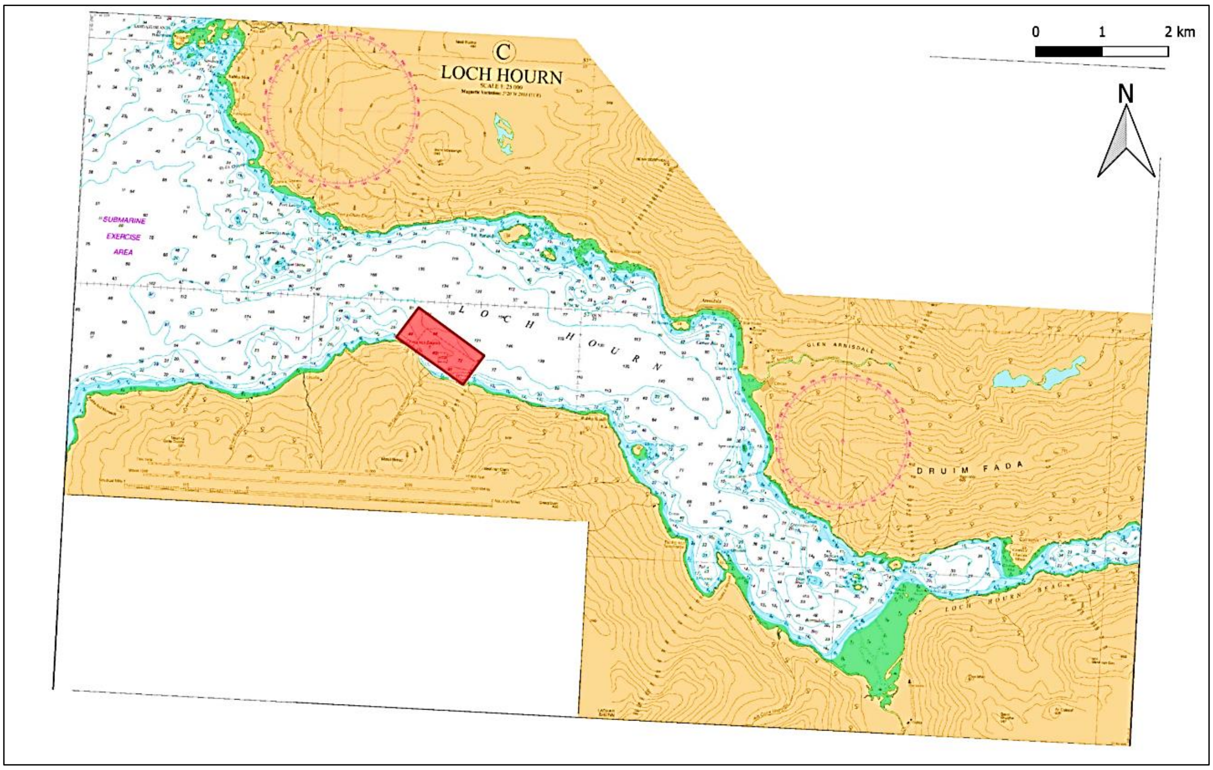


Figure 2 *Loch Hourn and salmon farm position.*

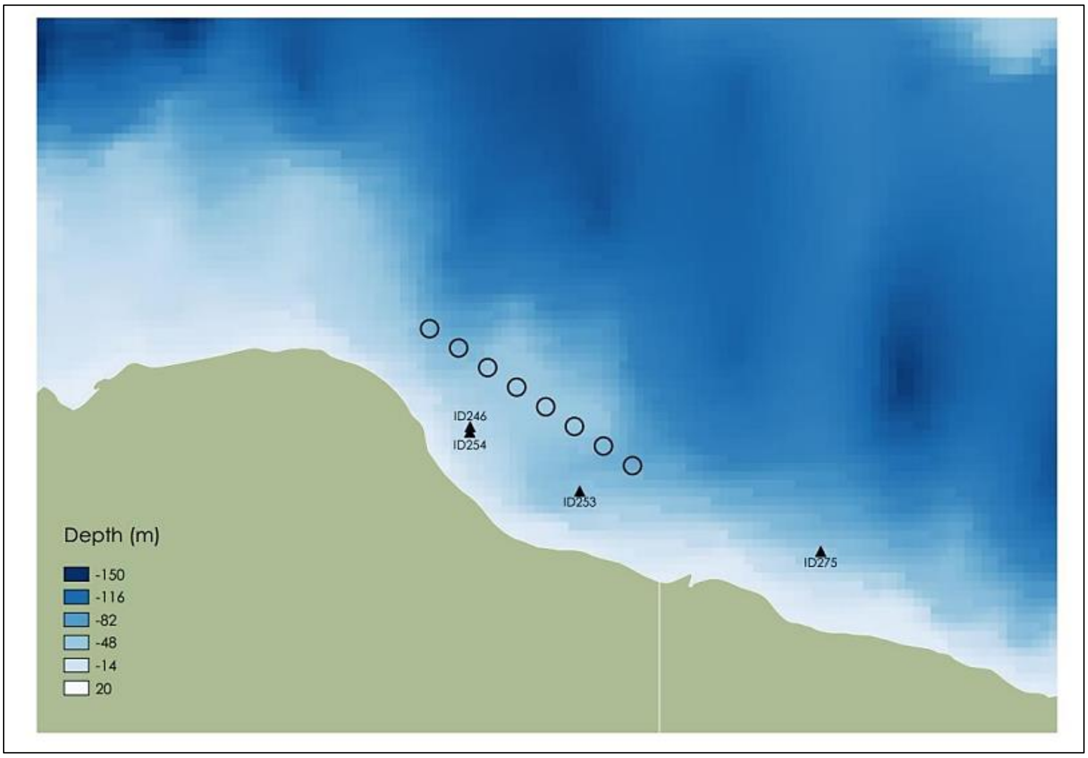


Figure 3 *Position of sea level and current speed meters in Loch Hourn. Observed data from flow meters with IDs 246, 253 and 254 were used for model comparisons.*

2.2 *Hydrodynamic data*

Both 2D and 3D approaches to the hydrodynamics modelling were undertaken. The 3D approach is used to provide current speed data for any sea lice, nutrients or bath treatment modelling. A 2D approach is adopted for waste modelling as this normally is assessed over and extended time period of around 90 days. A 3D approach for waste modelling would be computationally intractable.

The modelling approach in 3D was to employ the non-hydrostatic version of Telemac across the West Coast of Scotland, the extent of which is shown in Figure 4. 10 terrain-following vertical sigma layers are applied in the model and it includes tidal and meteorological forcing and stratification due to freshwater inflows and atmosphere-water heat exchange. Extensive validation and verification tests have previously been undertaken against physical data and inter-model comparisons with the Scottish Shelf Model (SSM) results, for details see [SCANLON, 2022].

Figure 5 shows the 2D mesh and model extent while the mesh in Loch Hourn is shown in Figure 6. The 2D model is run in vertically-averaged mode and model calibration has been carried out by varying the sea bed friction and adjusting the Telemac calibration parameters for tidal range and velocity. Tidal and meteorological forcing in 2D is identical to the techniques employed in the 3D case [SCANLON, 2022].

For each simulation, the model was “spun-up” for three days and the model state at the end of the 72-hour spin-up period was saved. The main simulations were “hot-started” from this stored field.

2.3 *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, 2022], digitised Admiralty charts and bathymetry information from the UK’s Digimap Ordnance Survey Collection [DOSC, 2022]. The bathymetry used in the model is shown in Figure 7.

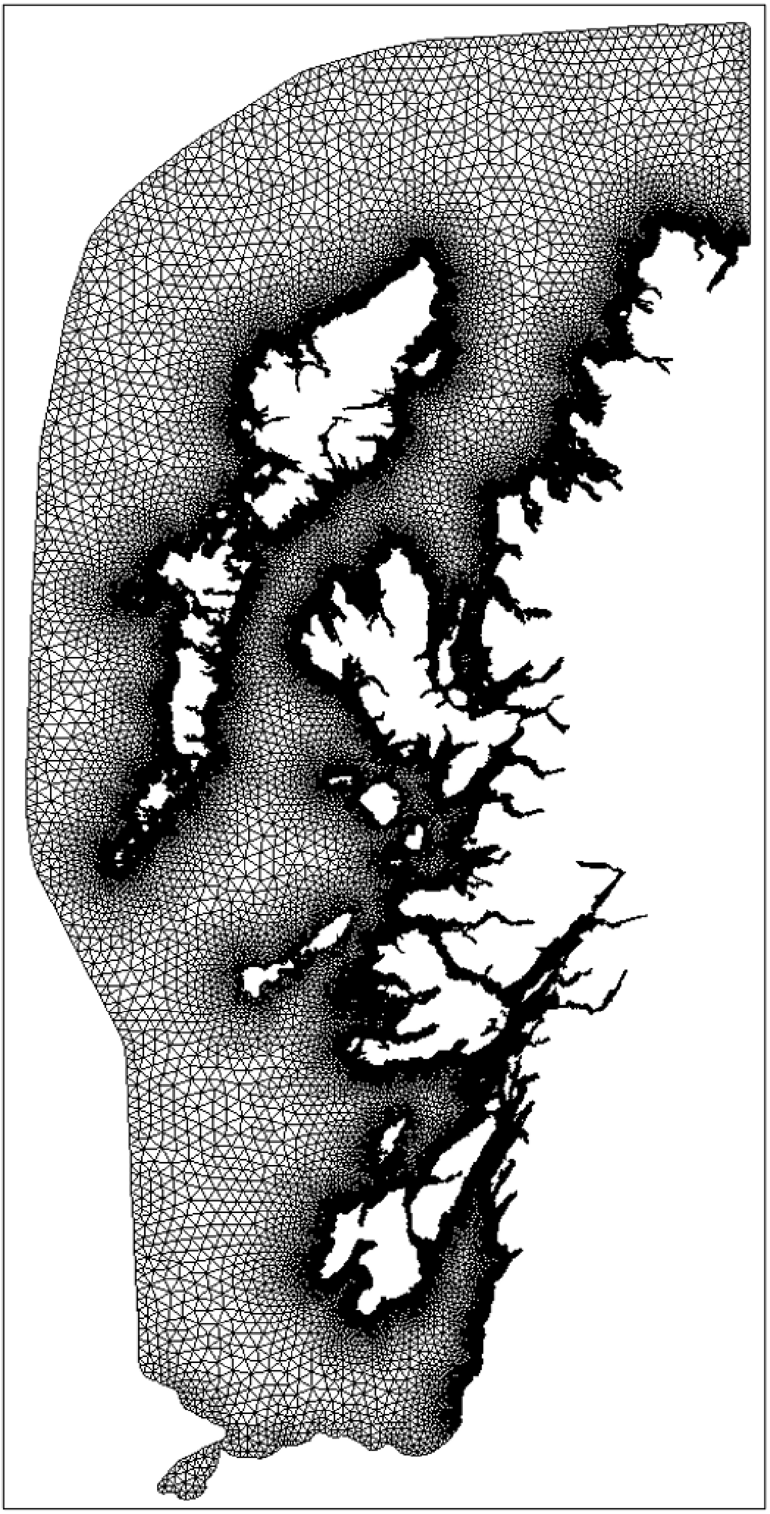


Figure 4 *Telemac 3D hydrodynamic mesh and model extent.*

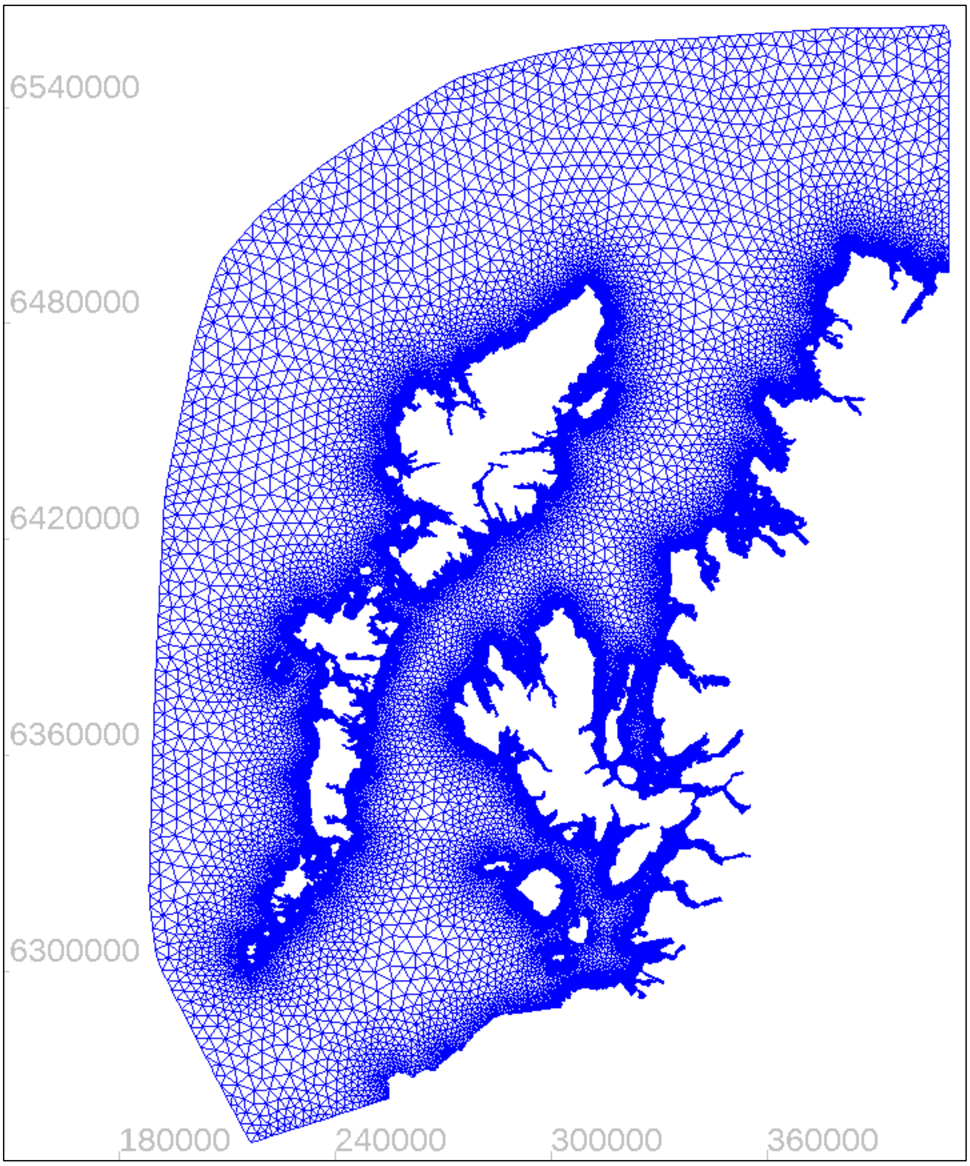


Figure 5 *Telemac 2D hydrodynamic mesh and model extent.*

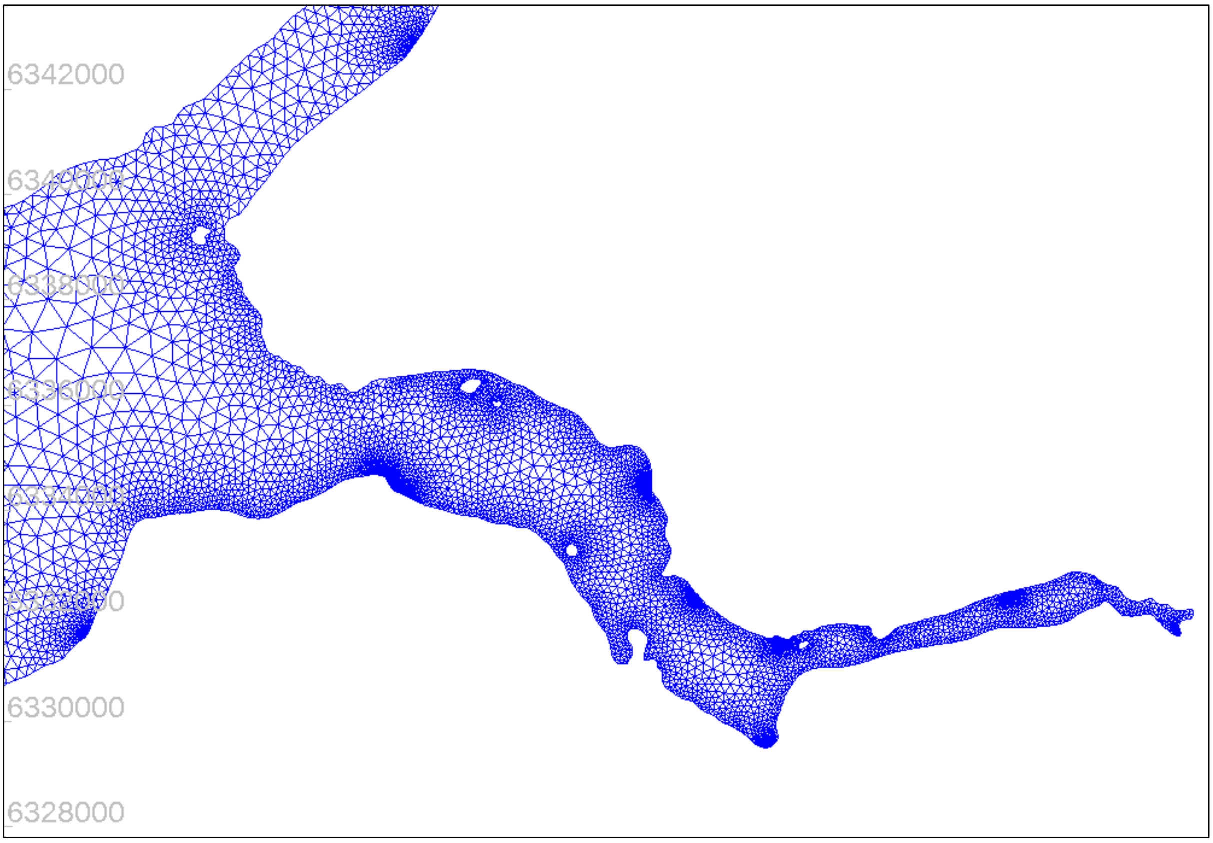


Figure 6 *Telemac hydrodynamic mesh in Loch Hourn for both 2D and 3D studies.*

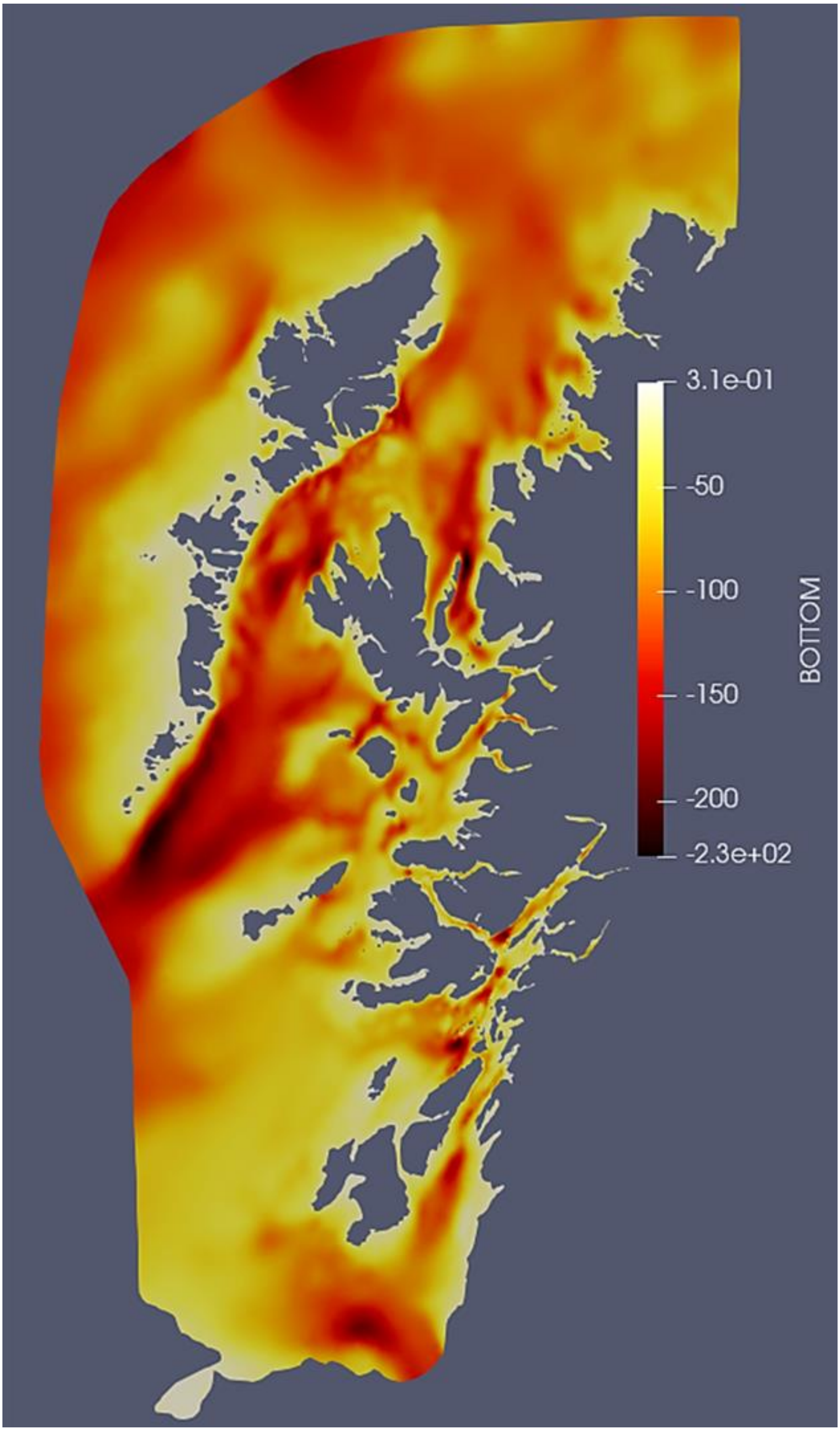


Figure 7 *West Coast model bathymetry (m).*

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 ≤ d2 ≤ 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, 2022]. All data refer to the surface layer.

3.1 2D Model – ID 254

At the ID_254 measurement location, the sea surface height was reasonably accurately modelled, with model skill of 0.99 (Figure 8 and Table 1). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.21 m and 0.25 m respectively are about 4.8% and 5.7% of the spring tide range, respectively. North and east components of velocity at the measurement location were satisfactorily reproduced by the model, with values of the model skill, d2, of about 0.46 and 0.45, respectively. The values of the MAE and RMSE being in the range 2 – 5 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 2D model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 9-13 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 ID_254 from 4^{th}-31^{st} December 2018.

	SSH	East	North
Skill, d2	0.99	0.45	0.46
Mean Absolute Error (MAE)	0.21	0.02 m/s	0.04 m/s
Root-Mean-Square Error (RMSE)	0.25	0.03 m/s	0.05 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 measurement location ID_254 from 4^{th}-31^{st} December 2018.

	SEPA Standard	Telemac2D	Result
SSH	+/- 10 % of Spring range (m)	5.7 %	✓
Current direction	+/- 30 deg	0.8 deg	✓
Timing of high water / phase	+/- 15 mins	14 mins	✓

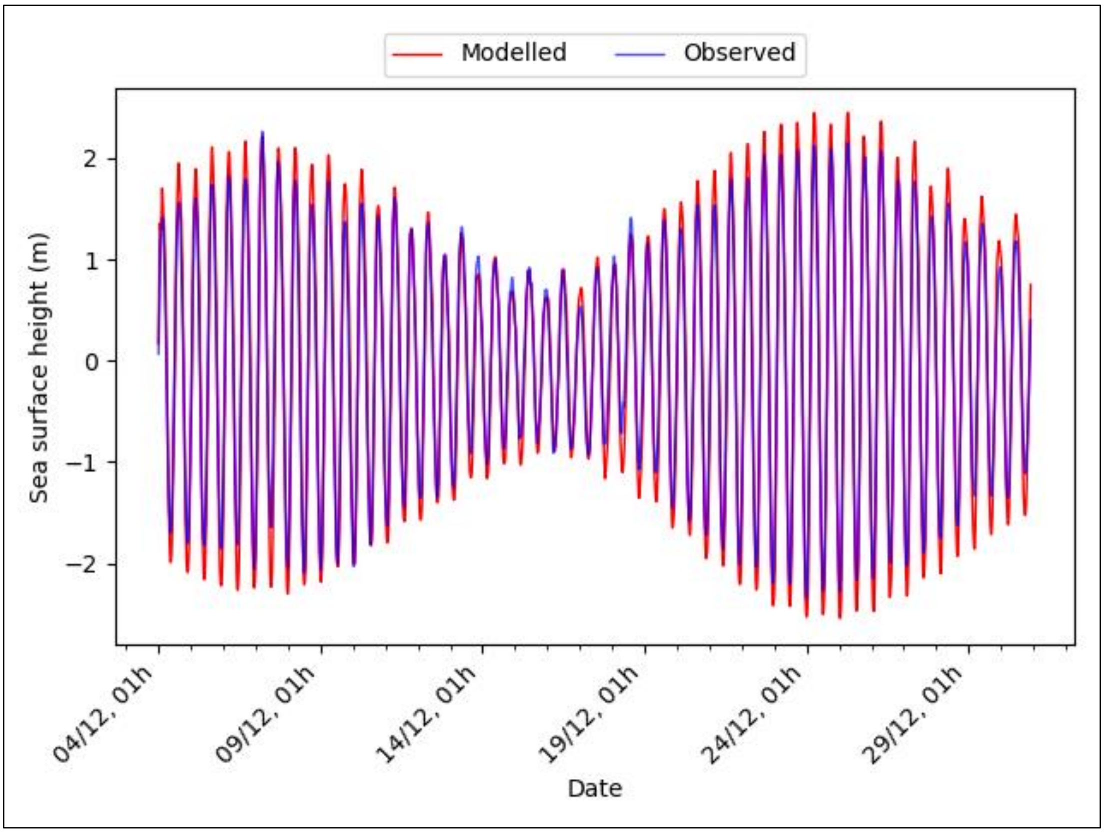


Figure 8 *Comparison between observed and modelled sea surface height from 4th-31st December 2018 (measurement ID_254).*

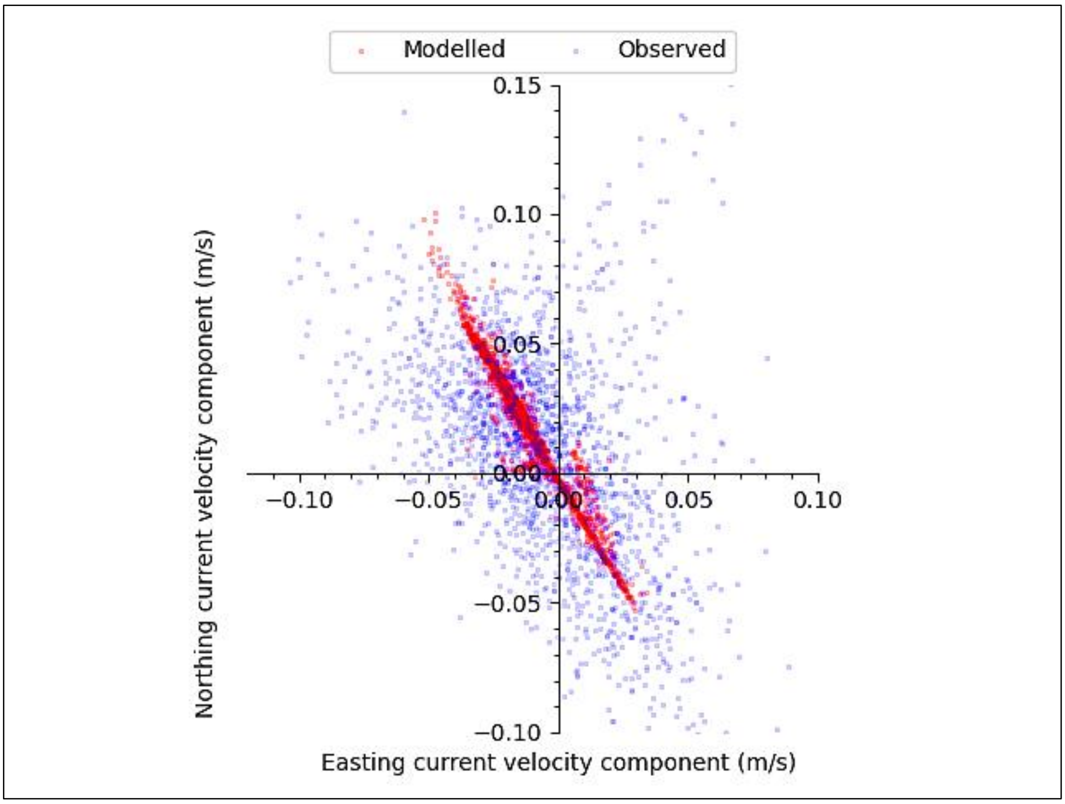


Figure 9 *Scatter plot of observed and modelled velocity from 4th-31st December 2018 (measurement ID_254).*

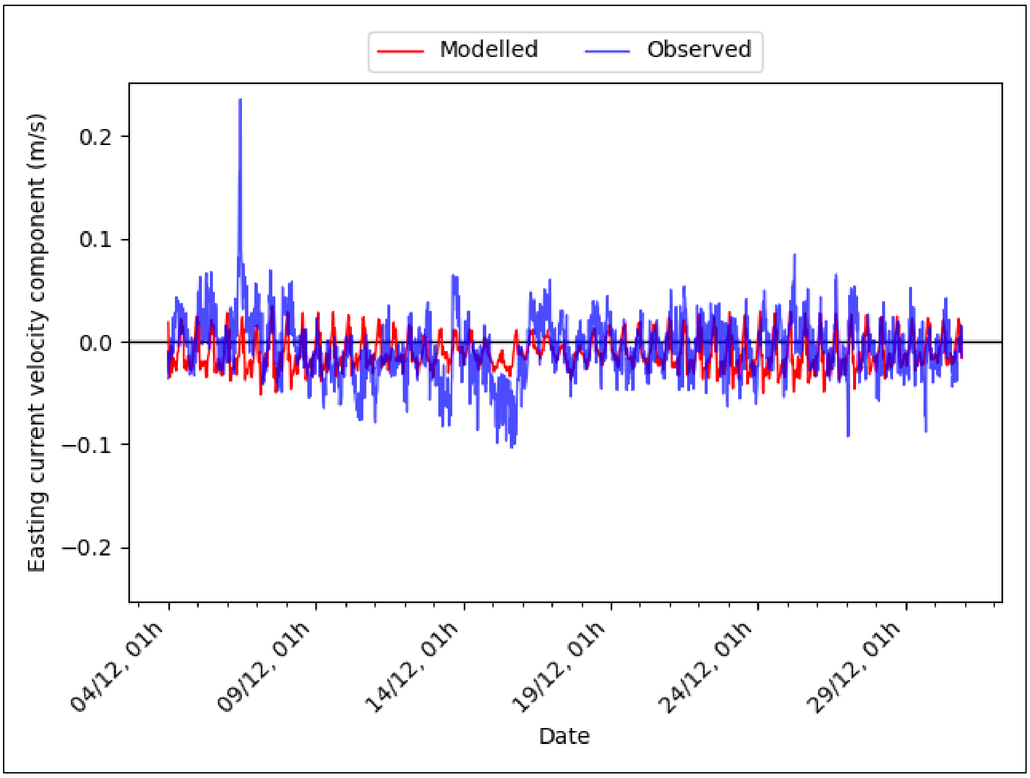


Figure 10 *Comparison between observed and modelled East velocity component from 4th-31st December 2018 (measurement ID_254).*

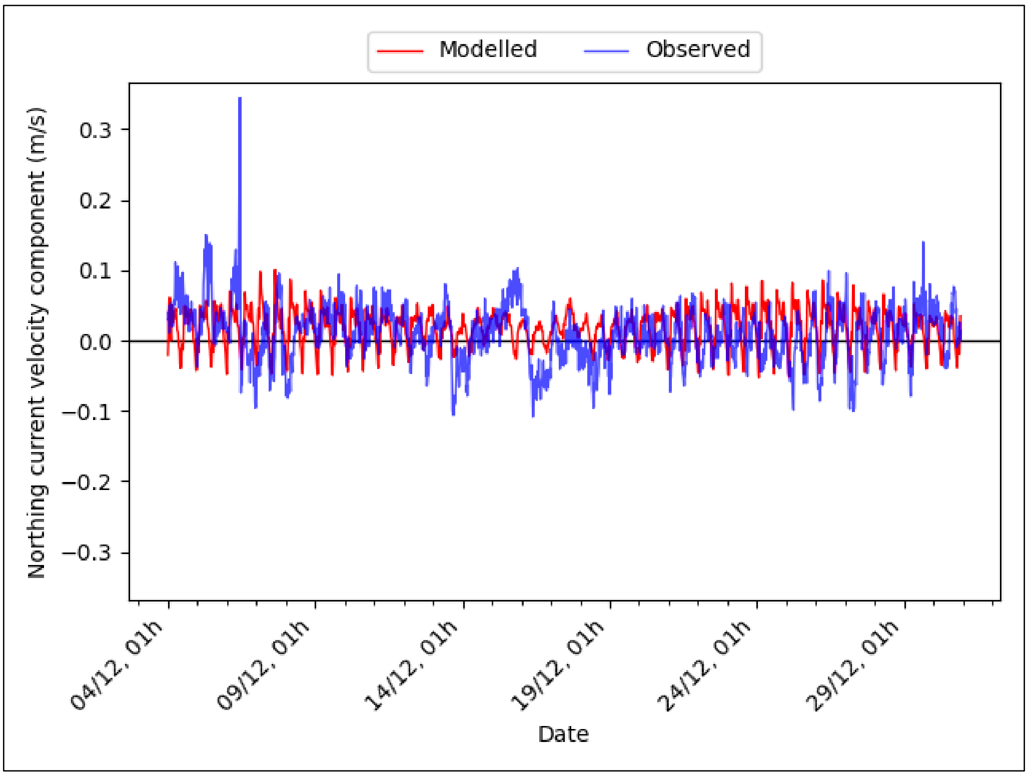


Figure 11 *Comparison between observed and modelled North velocity component from 4th-31st December 2018 (measurement ID_254).*

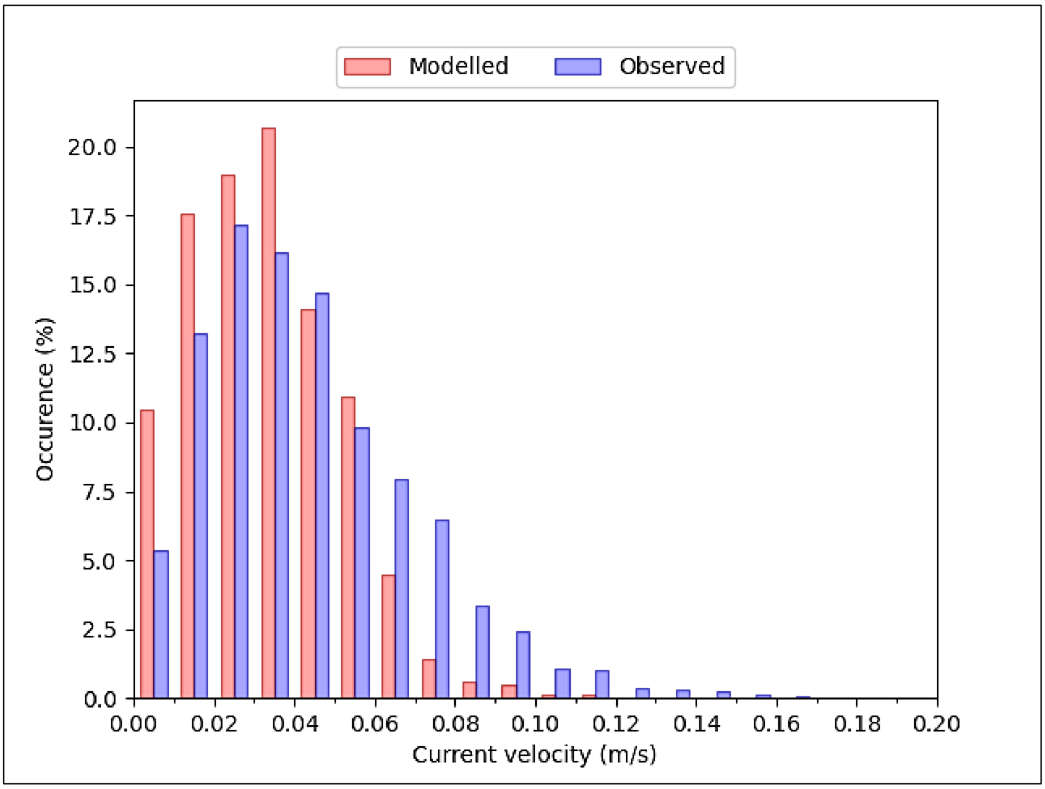


Figure 12 *Histogram of observed and modelled current speed component from 4th-31st December 2018 (measurement ID_254). Model skill d2 = 0.96.*

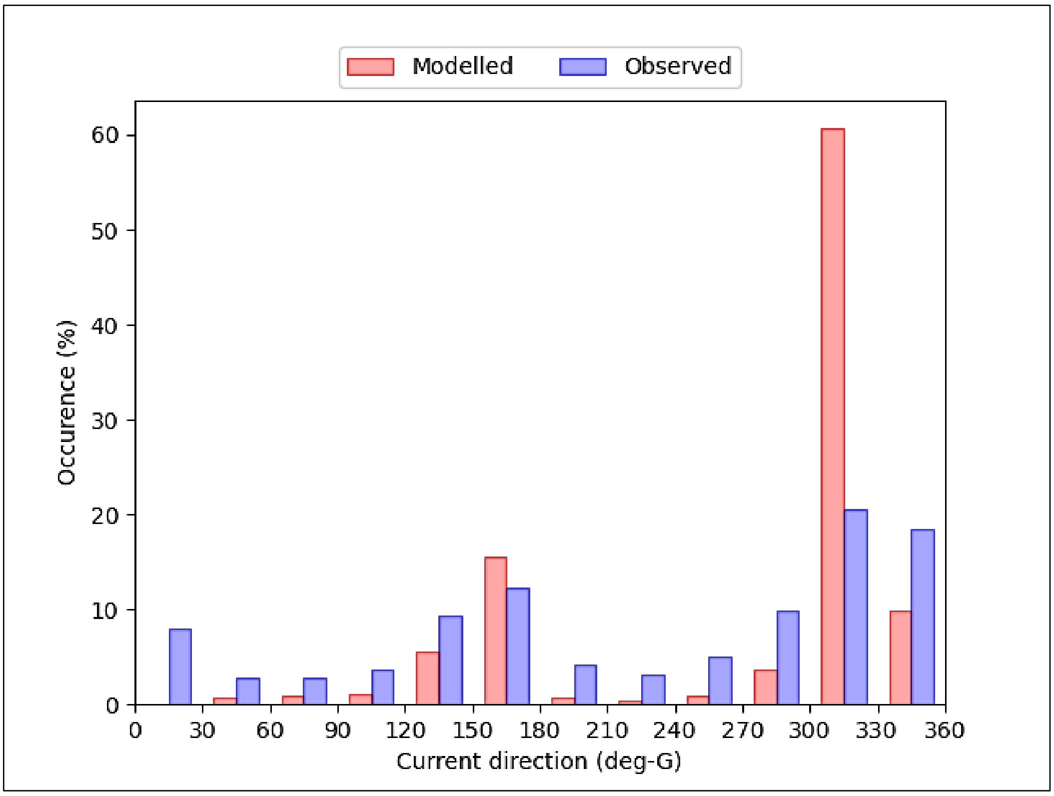


Figure 13 *Histogram of observed and modelled current direction from 4th-31st December 2018 (measurement ID_254). Model skill d2 = 0.66.*

3.2 2D Model – ID 253

At the ID_253 measurement location, the sea surface height was reasonably accurately modelled, with model skill of 0.99 (Figure 14 and Table 3). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.21 m and 0.25 m respectively are about 4.8% and 5.7% 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 0.47 and 0.44, respectively. The values of the MAE and RMSE being in the range 2 – 4 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 2D model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 15-19 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 ID_253 from 4^{th}-31^{st} December 2018.

	SSH	East	North
Skill, d2	0.99	0.44	0.47
Mean Absolute Error (MAE)	0.21	0.03 m/s	0.02 m/s
Root-Mean-Square Error (RMSE)	0.25	0.04 m/s	0.02 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 measurement location ID_253 from 4^{th}-31^{st} December 2018.

	SEPA Standard	Telemac2D	Result
SSH	+/- 10 % of Spring range (m)	5.7 %	✓
Current direction	+/- 30 deg	6.4 deg	✓
Timing of high water / phase	+/- 15 mins	13 mins	✓

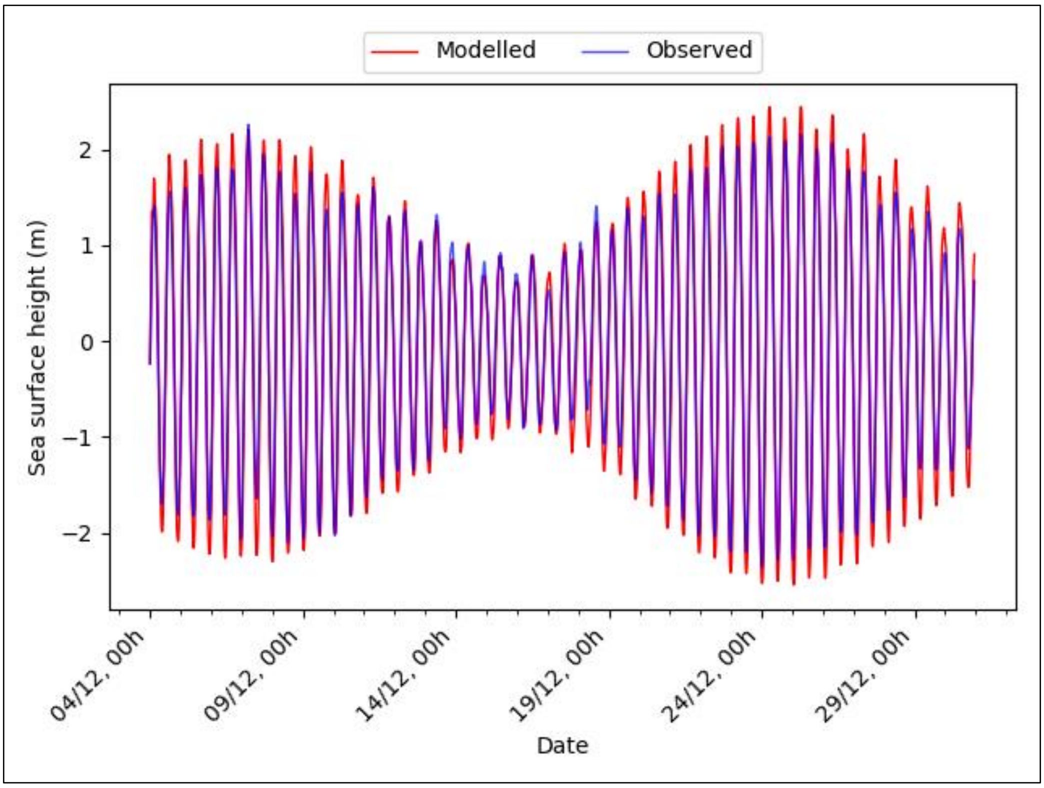


Figure 14 *Comparison between observed and modelled sea surface height from 4th-31st December 2018 (measurement ID_253).*

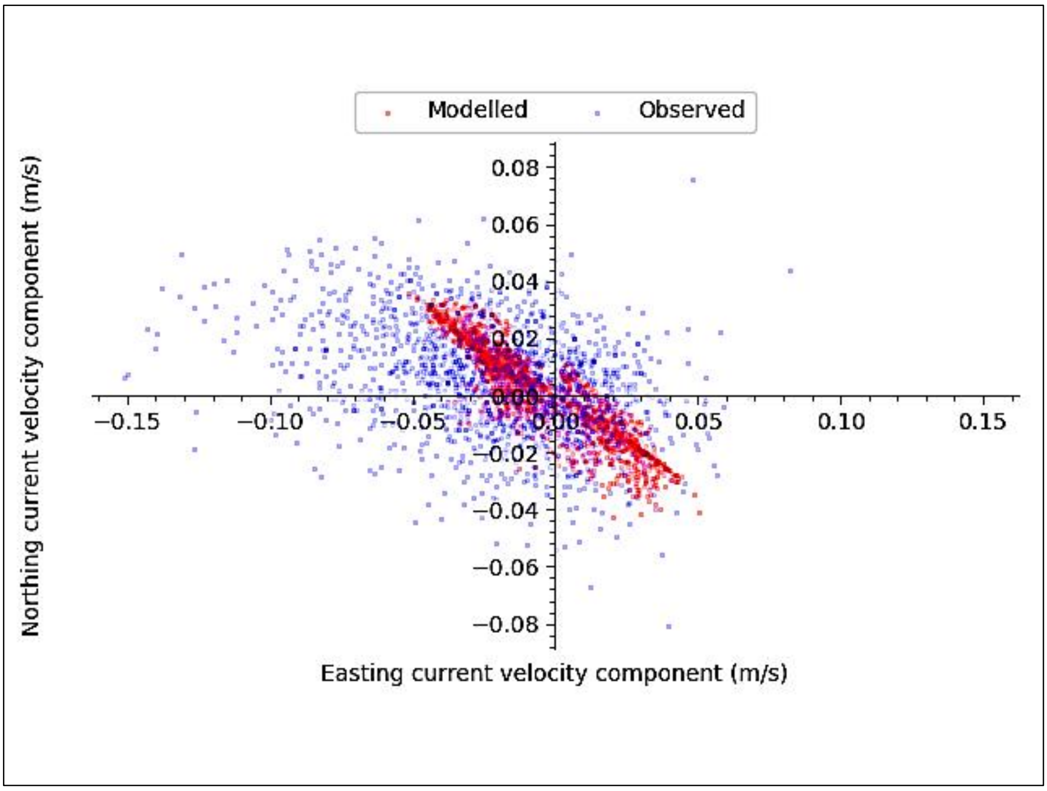


Figure 15 *Scatter plot of observed and modelled velocity from 4th-31st December 2018 (measurement ID_253).*

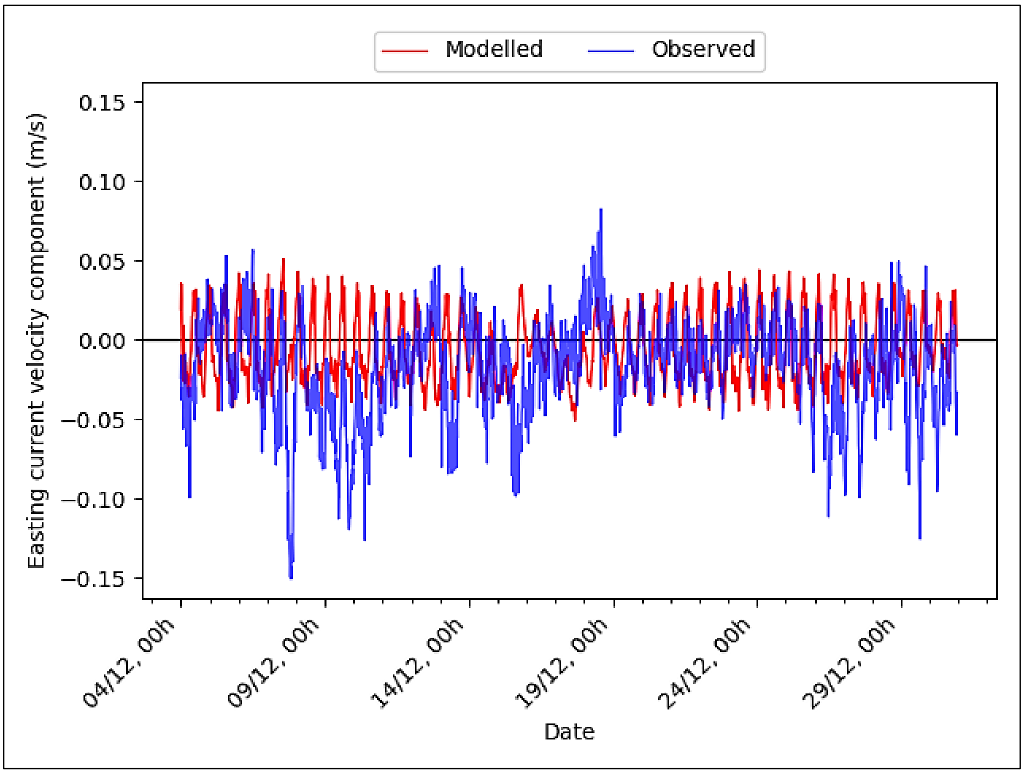


Figure 16 *Comparison between observed and modelled East velocity component from 4th-31st December 2018 (measurement ID_253).*

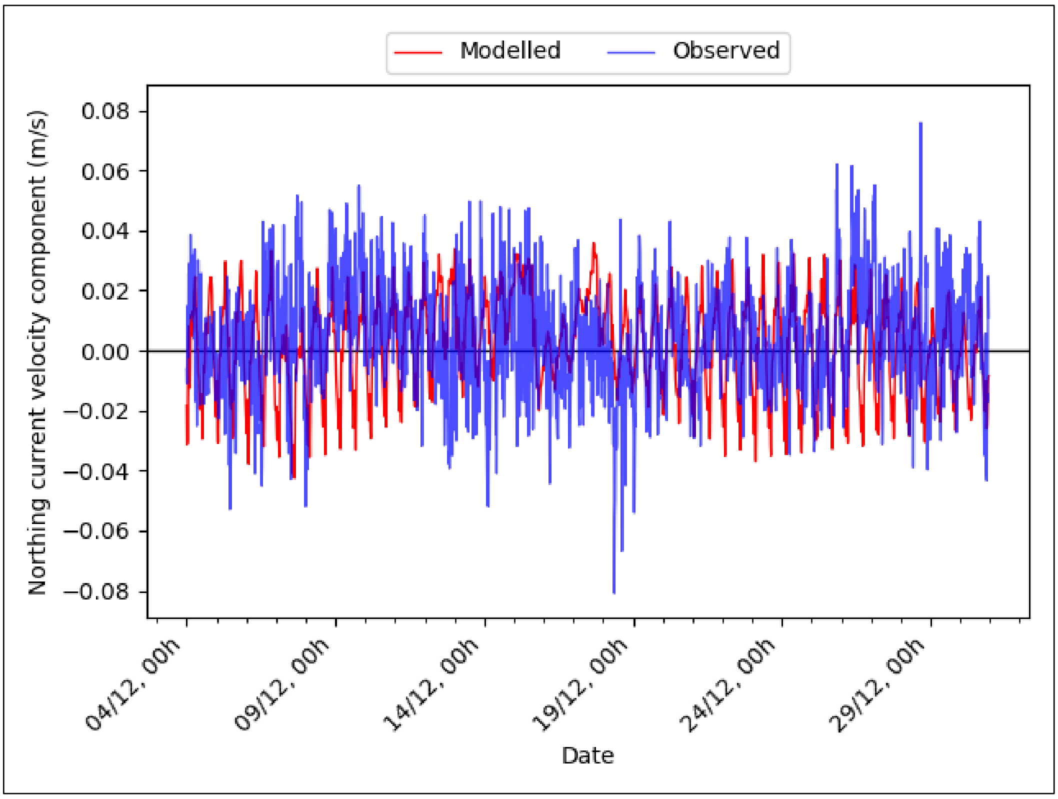


Figure 17 *Comparison between observed and modelled North velocity component from 4th-31st December 2018 (measurement ID_253).*

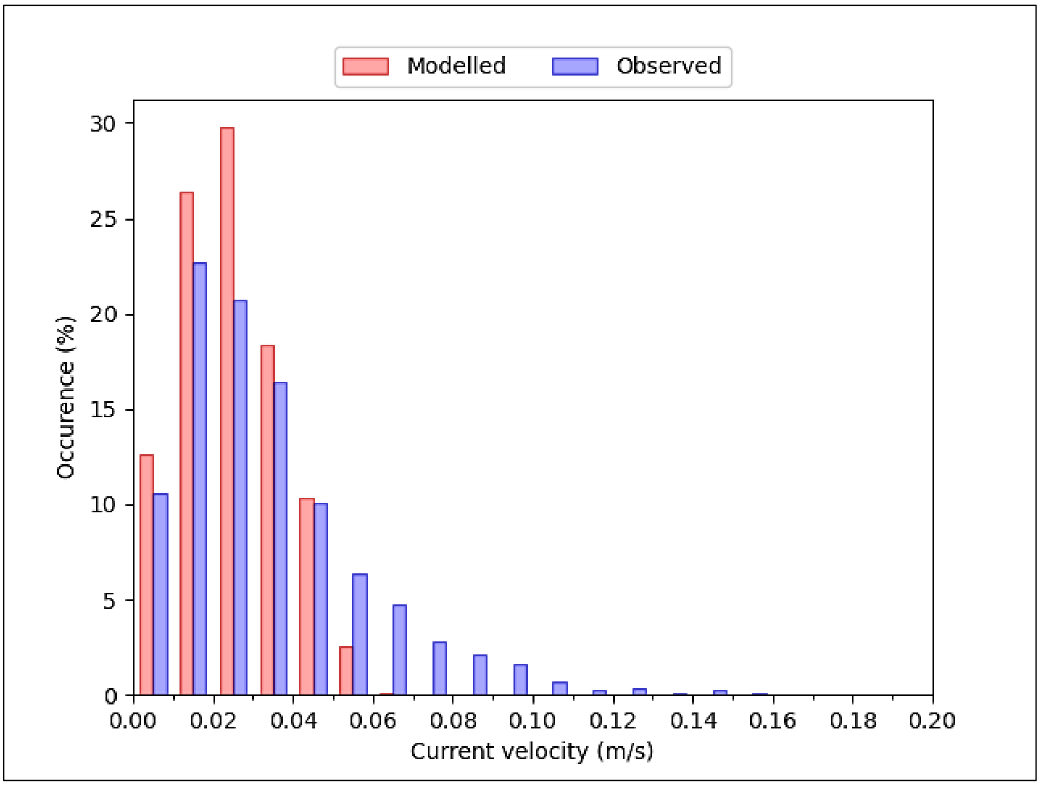


Figure 18 *Histogram of observed and modelled current speed component from 4th-31st December 2018 (measurement ID_253). Model skill d2 = 0.97.*

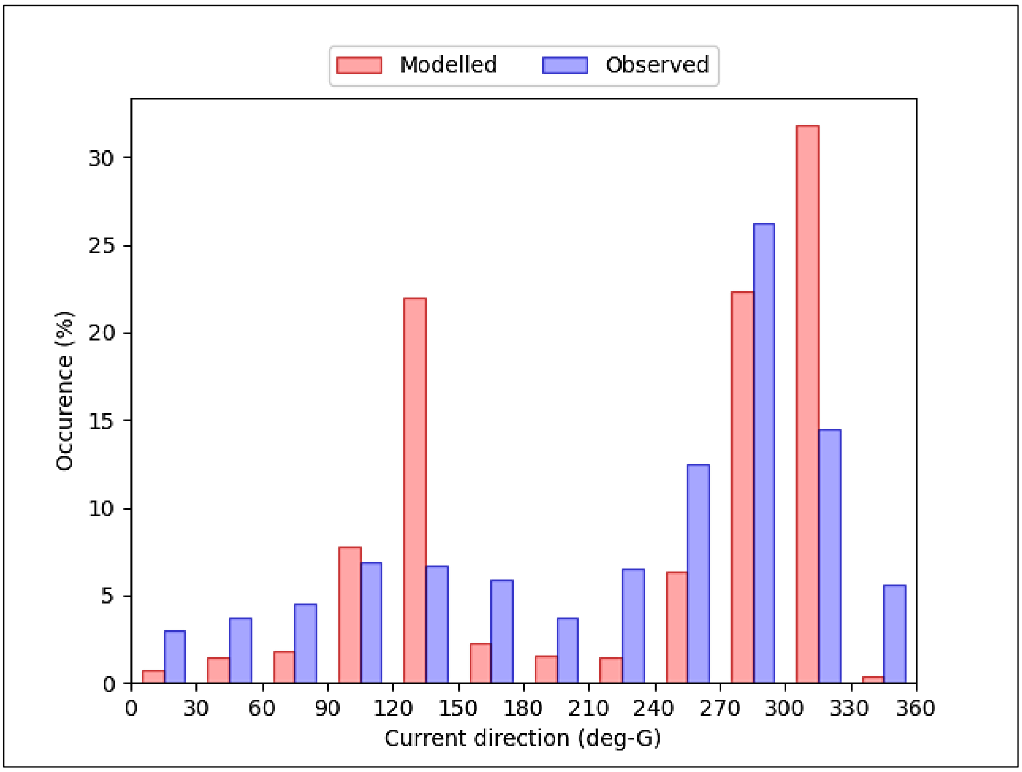


Figure 19 *Histogram of observed and modelled current direction from 4th-31st December 2018 (measurement ID_253). Model skill d2 = 0.77.*

3.3 3D Model – ID 246

At the ID_246 measurement location, the sea surface height was reasonably accurately modelled, with model skill of 0.99 (Figure 20 and Table 5). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.18 m and 0.24 m respectively are about 3.8% and 5.0% 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 0.51 and 0.46, respectively. The values of the MAE and RMSE being in the range 4 – 7 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]. 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 21-25 demonstrate that the modelled currents were broadly of the same speed and direction as the observed data.

Table 5. Model performance statistics for sea surface height (SSH), and East and North velocity at the measurement location ID_246 from 1st-28th October 2018.

	SSH	East	North
Skill, d2	0.99	0.46	0.51
Mean Absolute Error (MAE)	0.18	0.04 m/s	0.05 m/s
Root-Mean-Square Error (RMSE)	0.24	0.05 m/s	0.07 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 measurement location ID_246 from 1st-28th October 2018.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	5.0 %	✓
Current direction	+/- 30 deg	17.3 deg	✓
Timing of high water / phase	+/- 15 mins	17 mins	✗

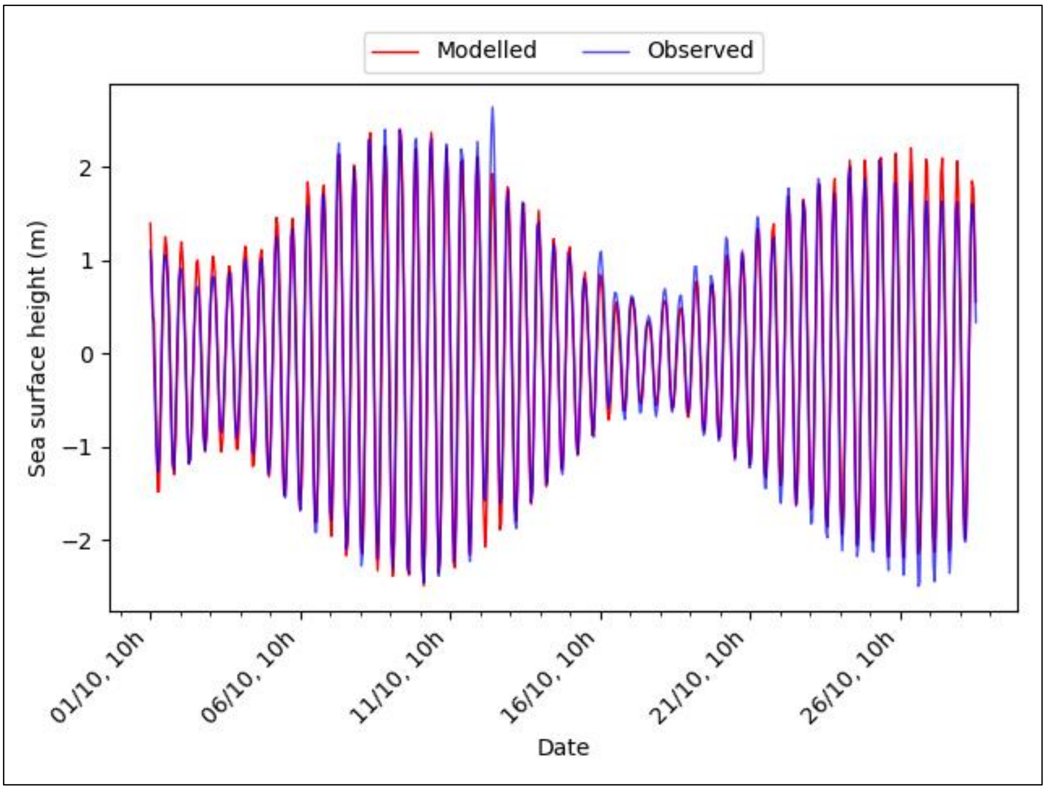


Figure 20 *Comparison between observed and modelled sea surface height from 1st-28th October 2018. (measurement ID_246).*

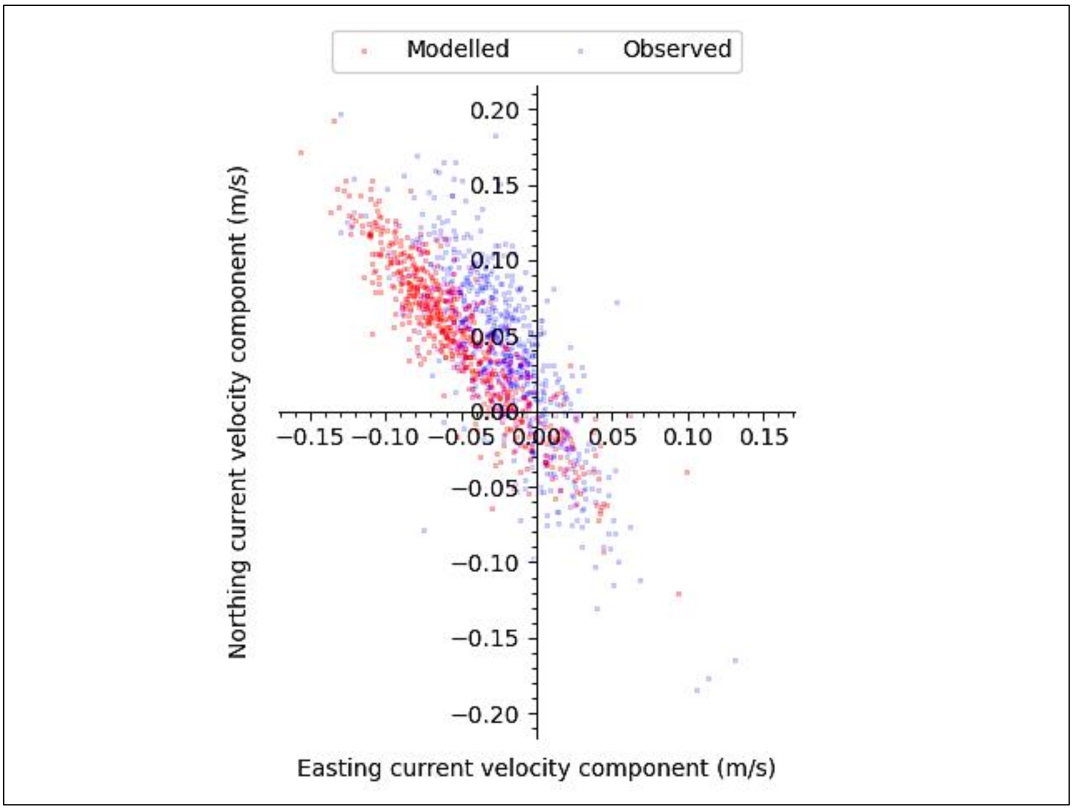


Figure 21 *Scatter plot of observed and modelled velocity from 1st-28th October 2018. (measurement ID_246).*

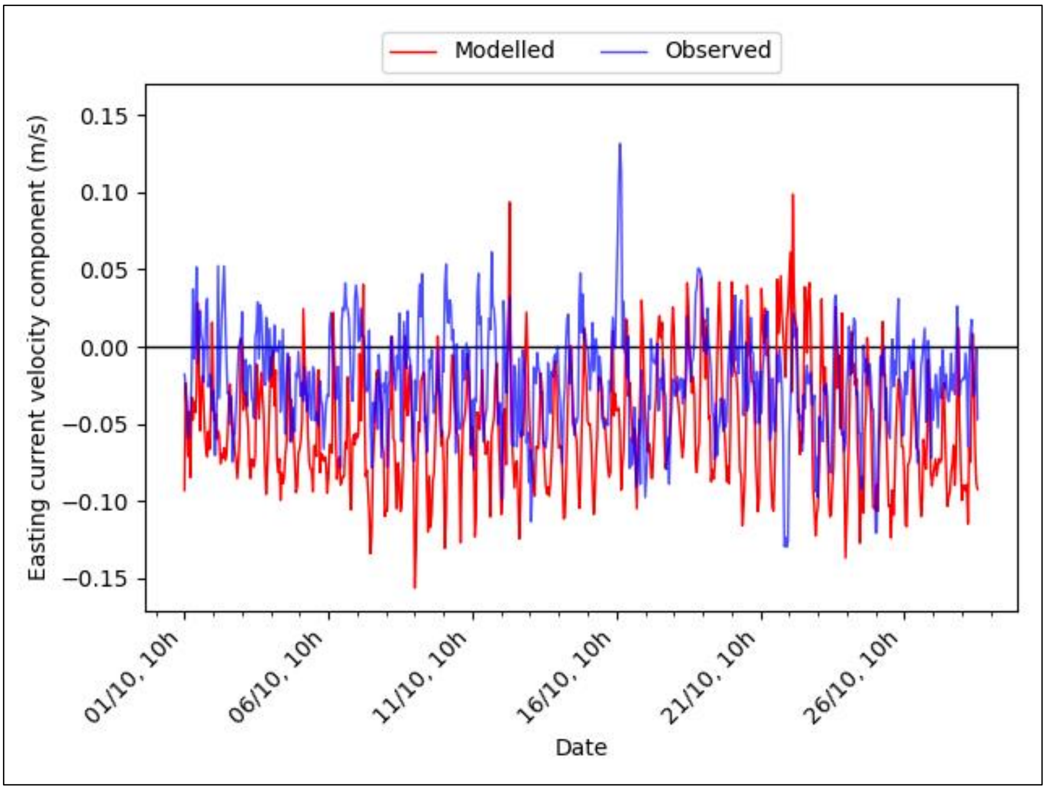


Figure 22 *Comparison between observed and modelled East velocity component from 1st-28th October 2018. (measurement ID_246).*

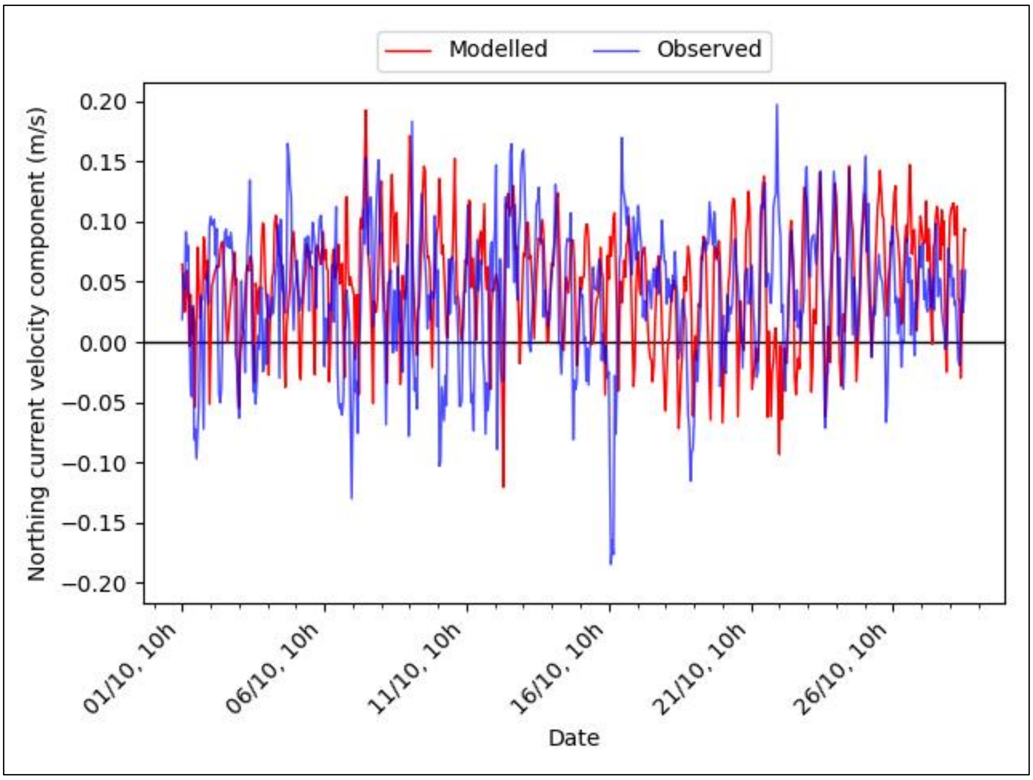


Figure 23 *Comparison between observed and modelled North velocity component from 1st-28th October 2018. (measurement ID_246).*

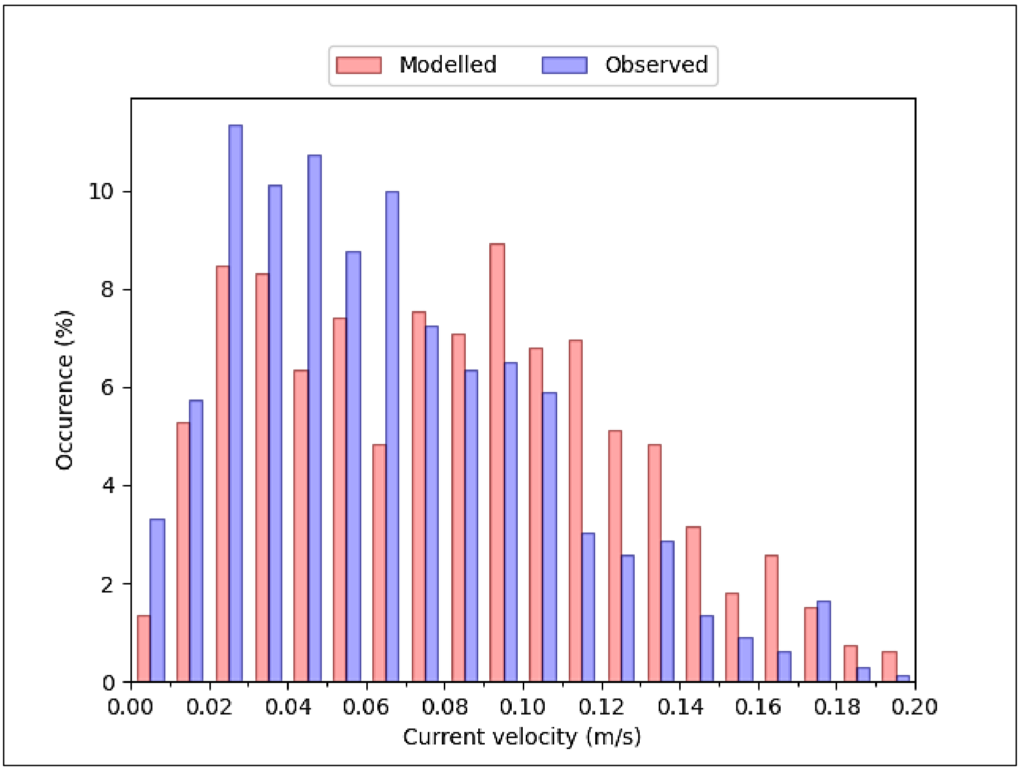


Figure 24 *Histogram of observed and modelled current speed component from 1st-28th October 2018. (measurement ID_246). Model skill d2 = 0.86.*

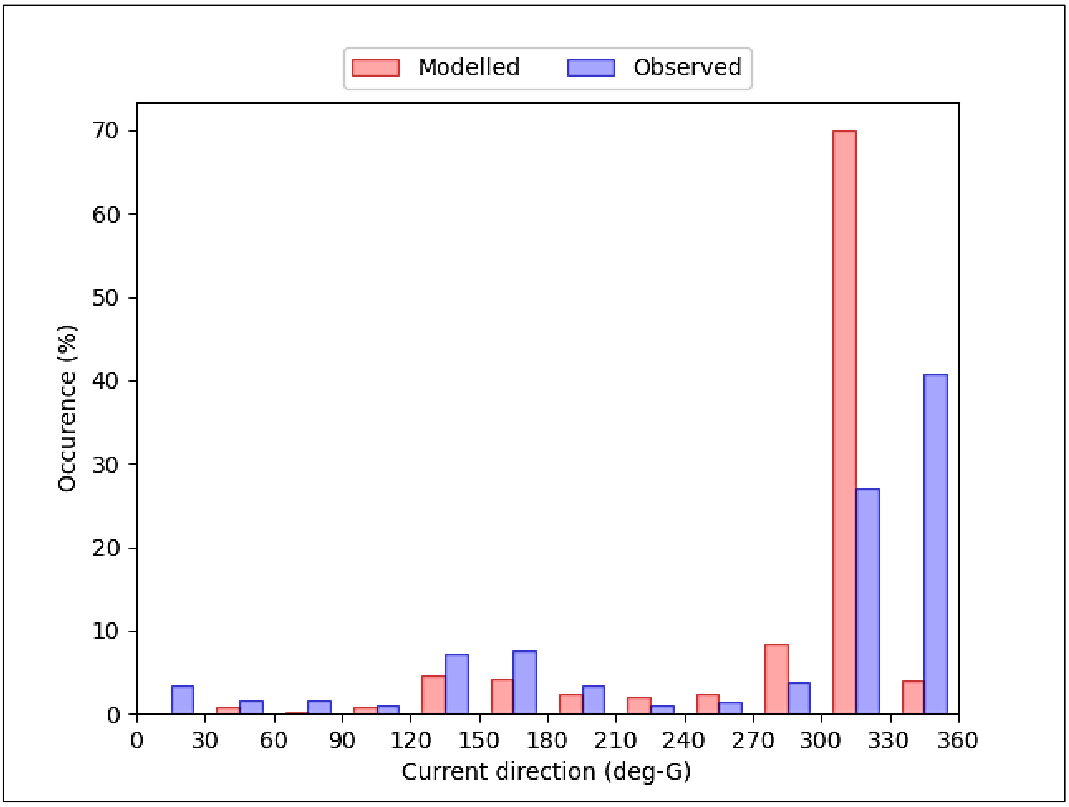


Figure 25 *Histogram of observed and modelled current direction from 1st-28th October 2018. (measurement ID_246). Model skill d2 = 0.64.*

Other examples of Python script output shown in Appendix A for the observed data at ID_253

4. Modelled Flow Fields in Loch Hourn

Modelled ebb and flood velocity vectors in Loch Hourn are illustrated in Figures 26 to 29. The Loch Hourn farm is subject to tidal currents flowing in and out of the loch system from the Sound of Sleat. However, 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 hydrodynamic shearing from the faster flowing Sound of Sleat water where it interacts with water at the mouth of Loch Hourn. Salinity effects are important too, with more brackish water in the surface layers being observed to often have a different magnitude and flow direction compared to the deeper, more saline water.

During ebb tide, a large counter-clockwise vortex is seen to form at the mouth of the loch in the surface layers (Figure 26), however, this is less evident in the middle-layers at the loch's mouth and there is little definition in the weak flow here (Figure 27). The main flows issuing from the loch appear in the surface layers along the southern and northern shores (Figure 26). However, these flows slow down and appear to be impeded by the eddies in the flow system at the mouth of the loch. In the lower layers, there is evidence of flow actually issuing into the loch during the ebb tide, likely being driven by salinity gradients.

At flood tide, the main flow into the loch is observed at the lower layers (Figure 29). The surface layer flow appears to be more complex with flow entering the loch along the southern shore but exiting along the northern shore at the mouth of the loch (Figure 28). An apparent battle of tidal versus salinity-driven currents appears to be taking place in the upper layers. Wind driven surface currents may also play a role here.

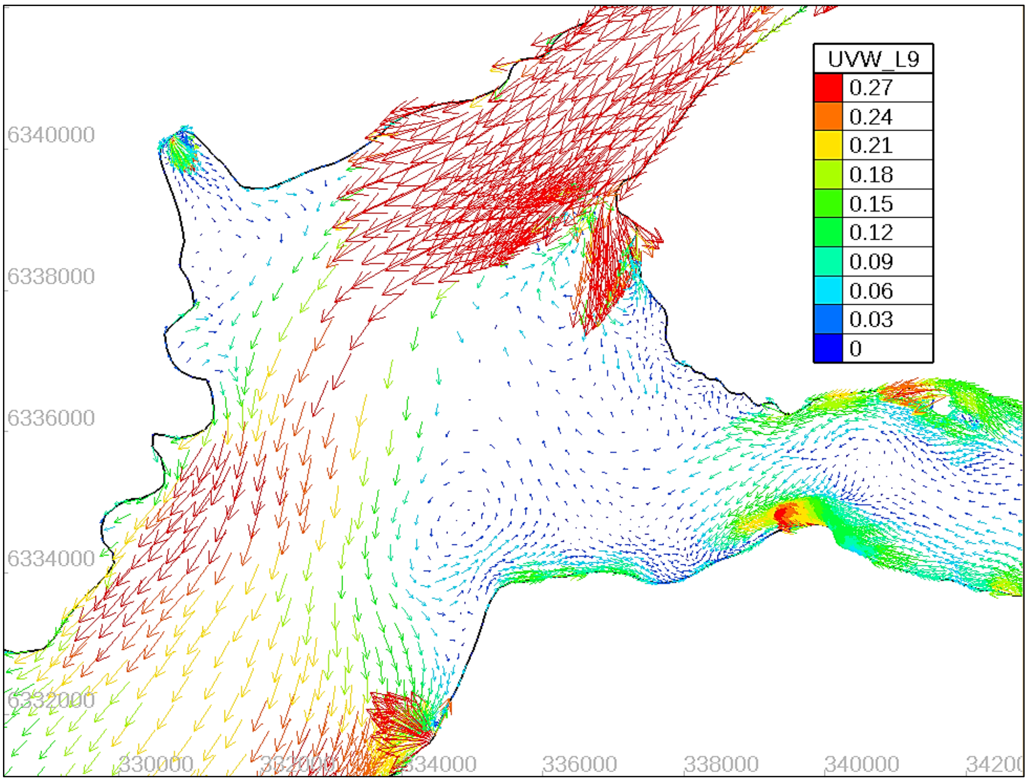


Figure 26 *Velocity vectors (m/s) in the near-surface layers of Loch Hourn during ebb tide on 8th May 2018 at 13h.*

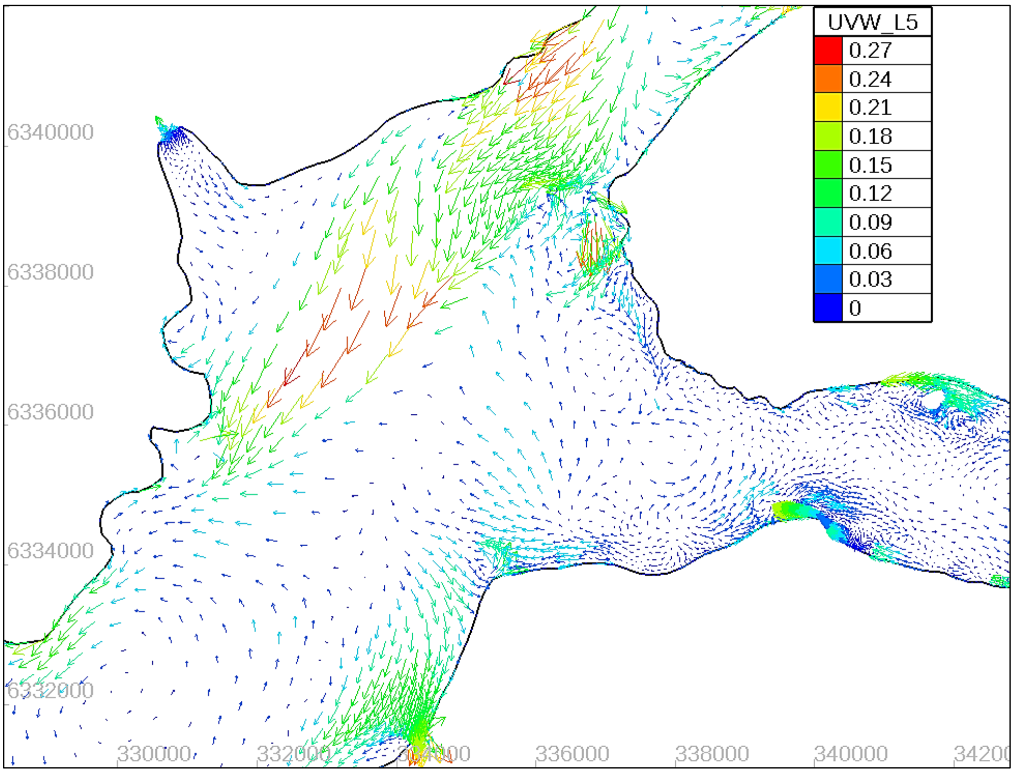


Figure 27 *Velocity vectors (m/s) in the middle layers of Loch Hourn during ebb tide on 8th May 2018 at 13h.*

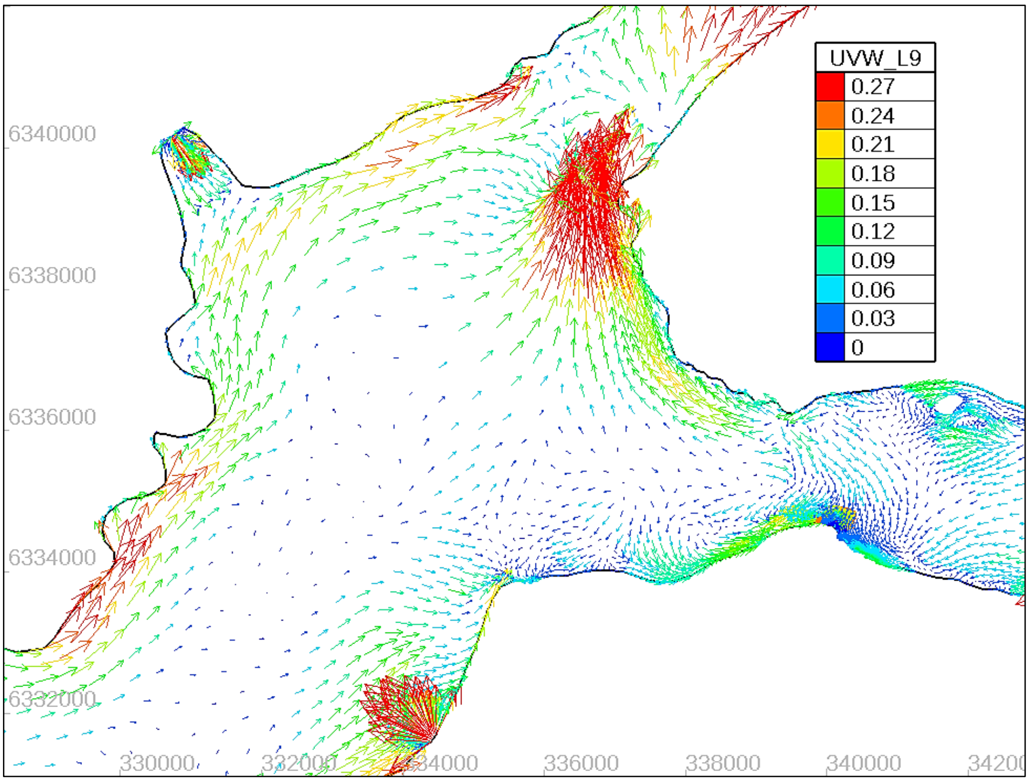


Figure 28 *Velocity vectors (m/s) in the near-surface layers of Loch Hourn during flood tide on 13th May 2018 at 6h.*

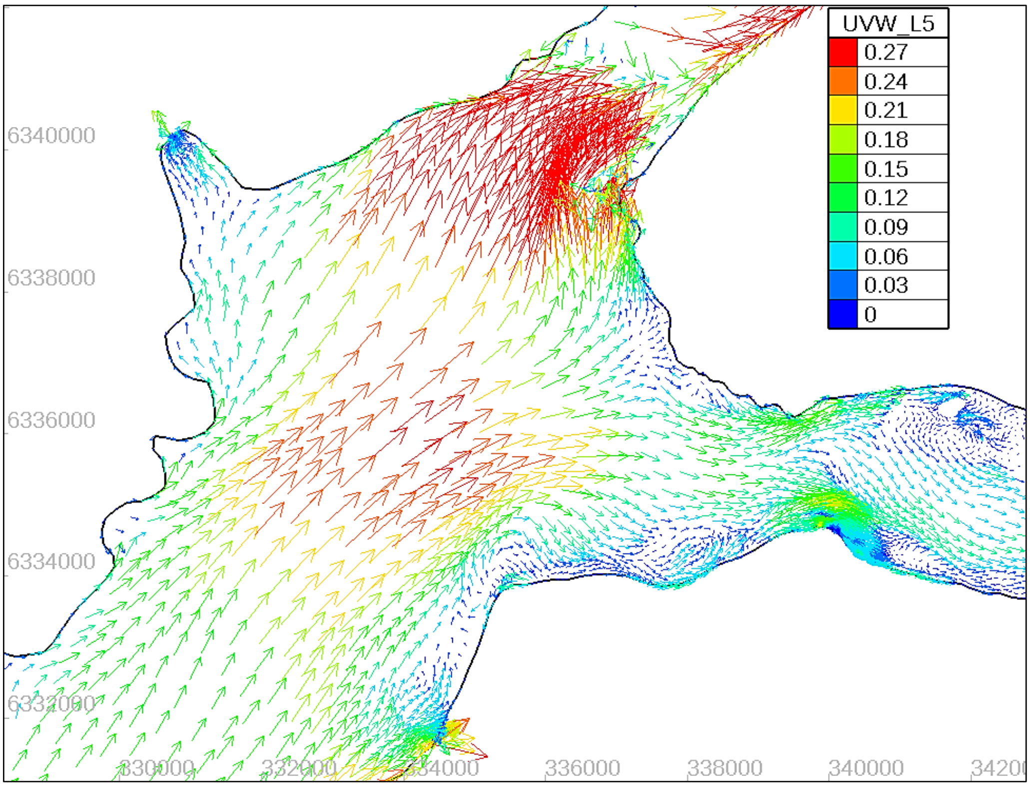


Figure 29 *Velocity vectors (m/s) in the middle layers of Loch Hourn during flood tide on 13th May 2018 at 6h.*

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, 2022]. The hydrodynamic models, generated using the Telemac software, correctly simulate the propagation of the tide over the West Coast and both 2D and 3D approaches provide a reasonable description of the flow currents within Loch Hourn 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 and around Loch Hourn is shown to exhibit strong three-dimensionality with the competing effects of tides, winds, salinity and temperature evident.

References

[CLAWS, 2022], https://claws-scot.github.io/ - accessed 20th Nov. 2022.

[DOSC, 2022], https://digimap.edina.ac.uk/marine - accessed 28th July 2022.

[SCANLON, 2022], Scanlon, T. J., *A Hydrodynamic Model of the West Coast of Scotland – Validation Case Studies*, 2022.

[SEPA, 2019], https://www.sepa.org.uk/media/450279/regulatory-modelling-guidance-for-the-aquaculture-sector.pdf, accessed 20th Nov. 2022.

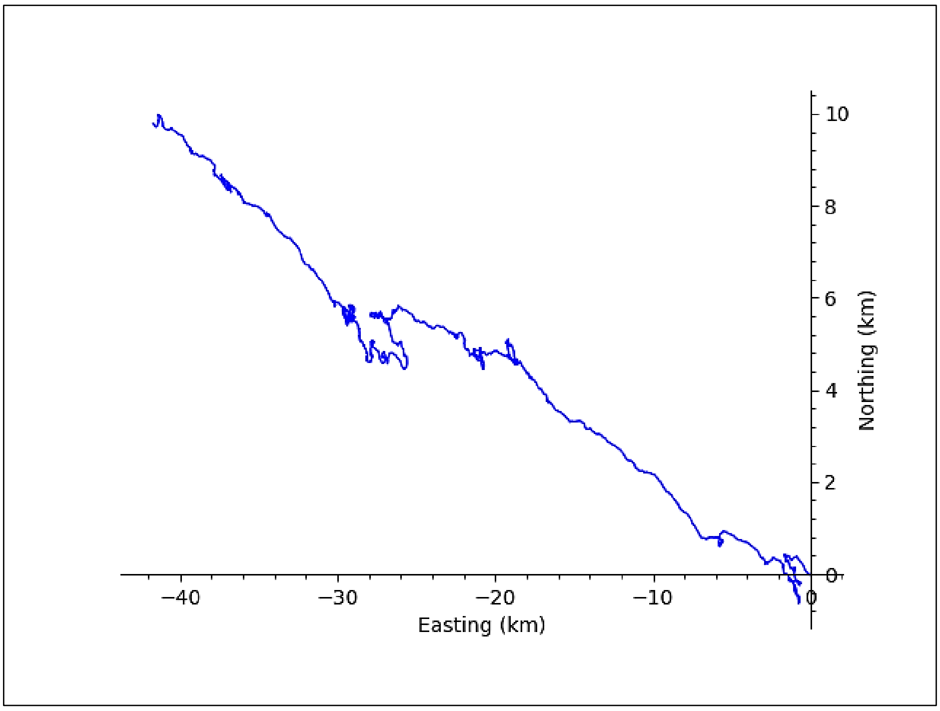
[SSM, 2022], http://www.marine.gov.scot/themes/scottish-shelf-model - accessed 28th July 2022.

[Telemac, 2022], http://www.opentelemac.org/ - accessed 20th Nov. 2022

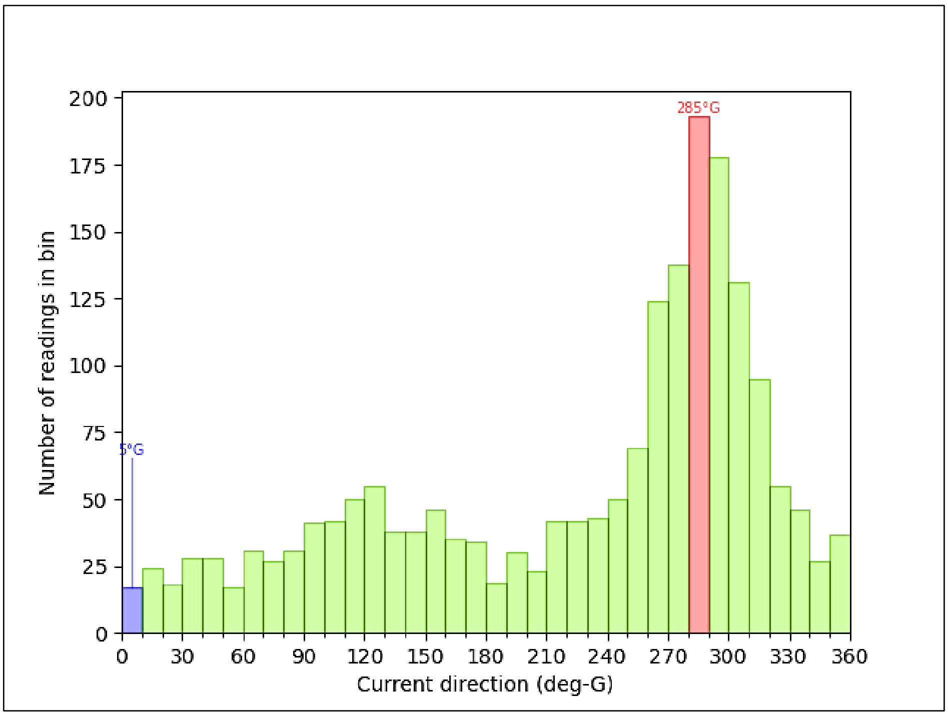
[WILLMOTT, 1985] Willmott, C. J.; Ackleson, S. G.; Davis, R. E.; Feddema, J. J.; Klink, K. M.; Legates, D. R. O'Donnell, J.; Rowe, C. M. 1985. Statistics for evaluation and comparison of models, J. Geophys. Res., 90, 8995– 9005.

APPENDIX A

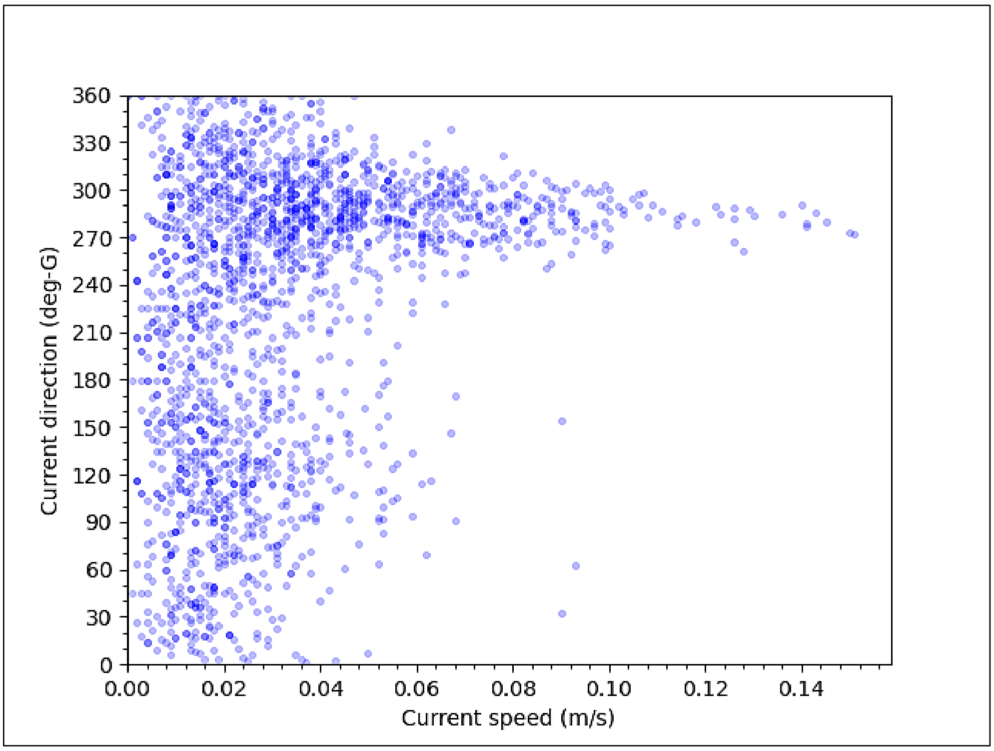
Examples of additional plots created using the post-processing Python scripts in CLAWS for the observed data at ID_253 are shown below:



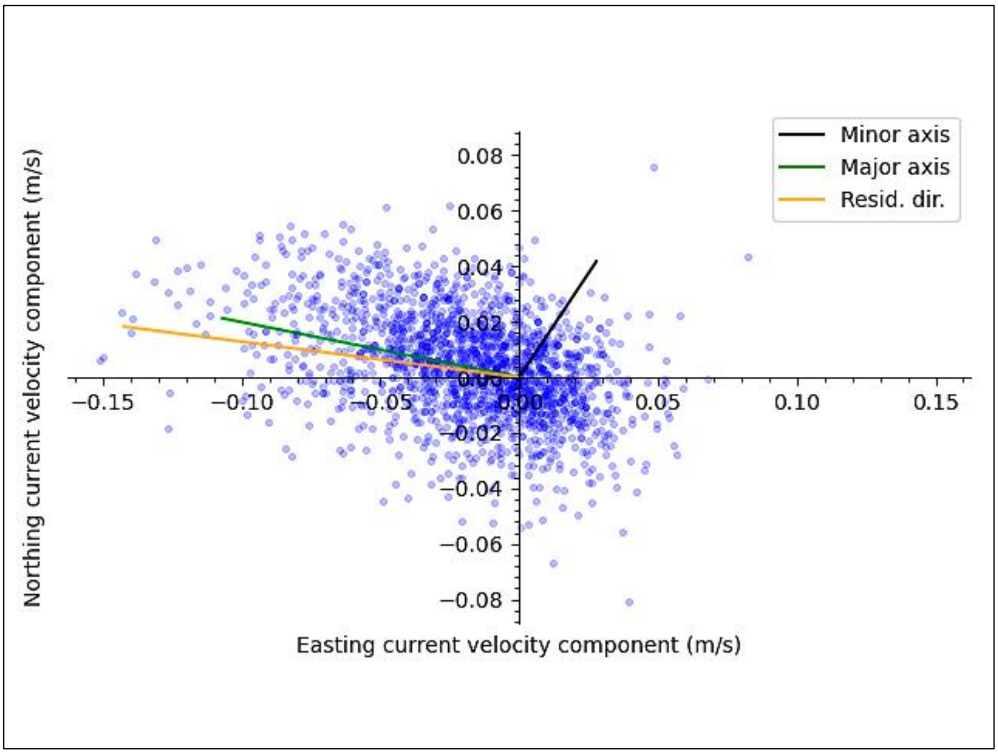
A.1 Cumulative vector



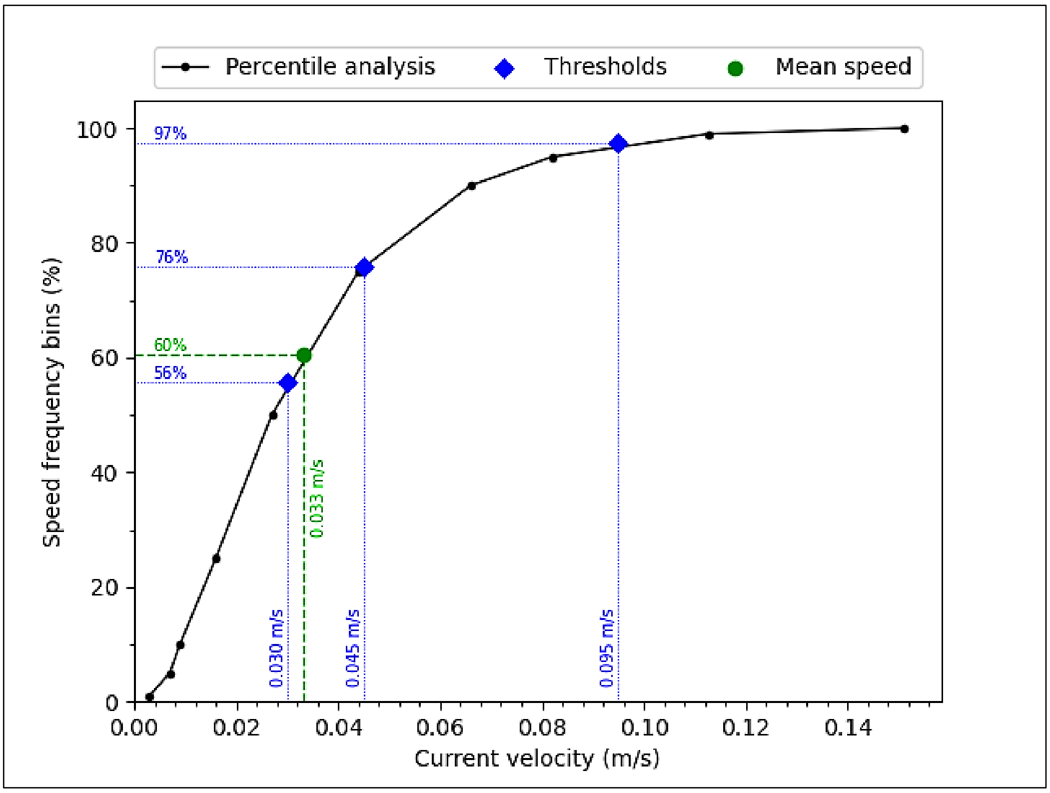
A.2 Flow direction bar graph



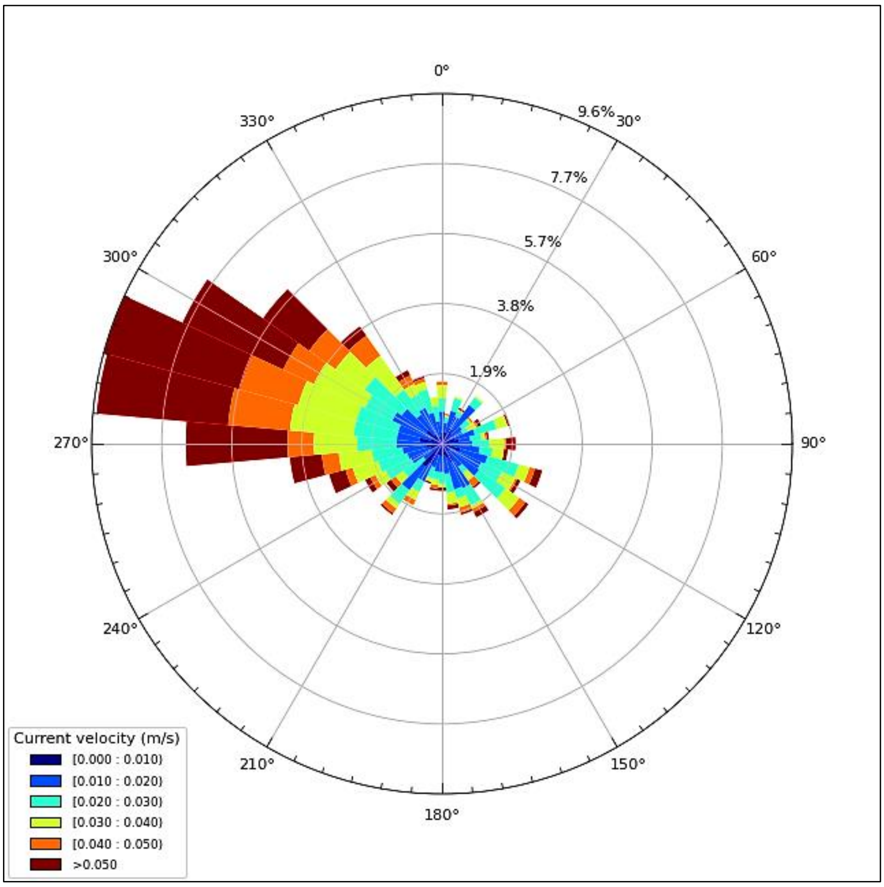
A.3 Direction vs current speed



A.4 Easting vs Northing velocity



A.5 Speed percentiles



A.6 Ocean Current rose