Firth of Forth Hydrodynamics Model Validation

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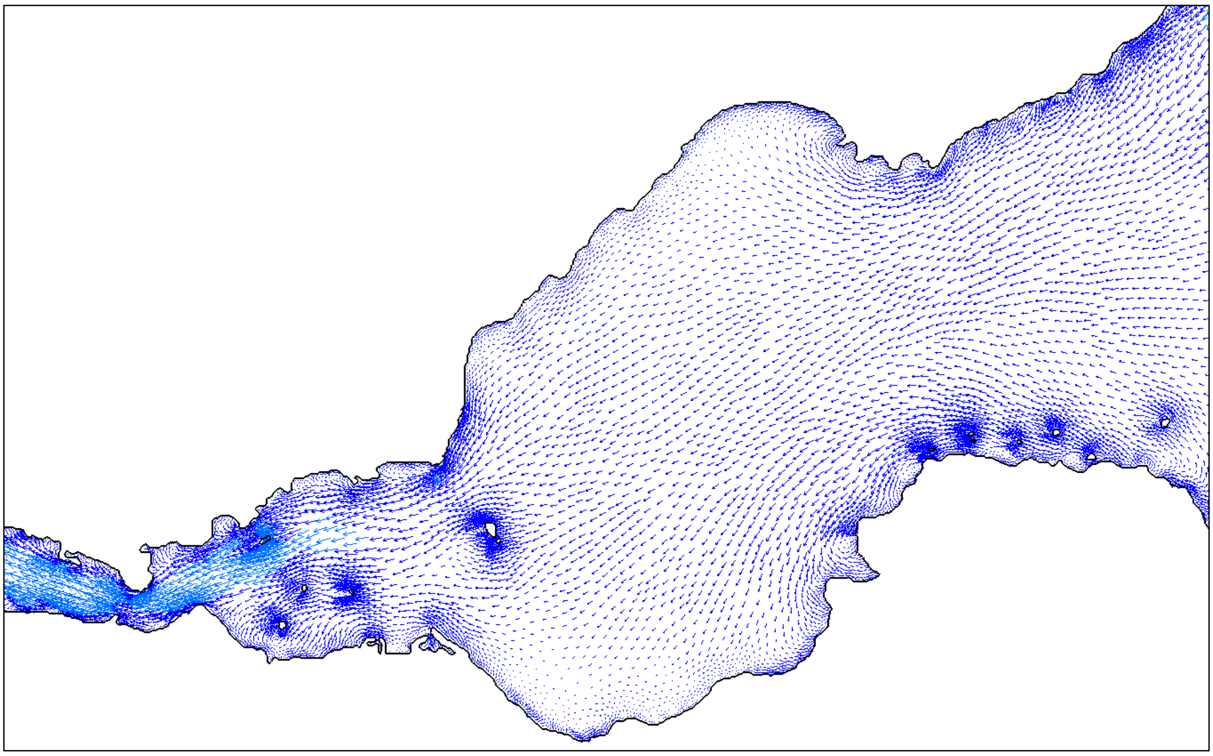

Executive Summary

A three-dimensional hydrodynamic (HD) model of the Firth of Forth and Forth estuary has been constructed using the Telemac code [TELEMAC, 2024]. The 3D model extends from the Kincardine bridge in the West into the North Sea, covering coastal areas to the North coast of Fife and Eyemouth in the East. 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 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 water surface 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 across the firth, utilized data lifted from the United Kingdom Hydrographic Office (UKHO) Admiralty Total Tide (ATT) package [ATT, 2024].

The model correctly simulates tide propagation over the Firth of Forths 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 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].

The model provides general insight into spatial and temporal variations in the flow environment in the Firth of Forth and Forth estuary. It offers a suitable basis for assessing near-field and far-field dispersion effects of particulate biological matter such as Escherichia coli (E. coli).

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 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 E. coli emanating from sewage spillages from combined sewer overflows (CSOs) in the Firth of Forth. The E. coli modelling is reported elsewhere and this report focuses on the hydrodynamics validation.

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

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 physical observation and predictions.

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 Firth of Forth, the extent of which is shown in Figures 1-2. 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 0.5 million elements were used in the model. Values of wind speed, direction and air temperature were gathered from the online resource [TIME_DATE, 2024].

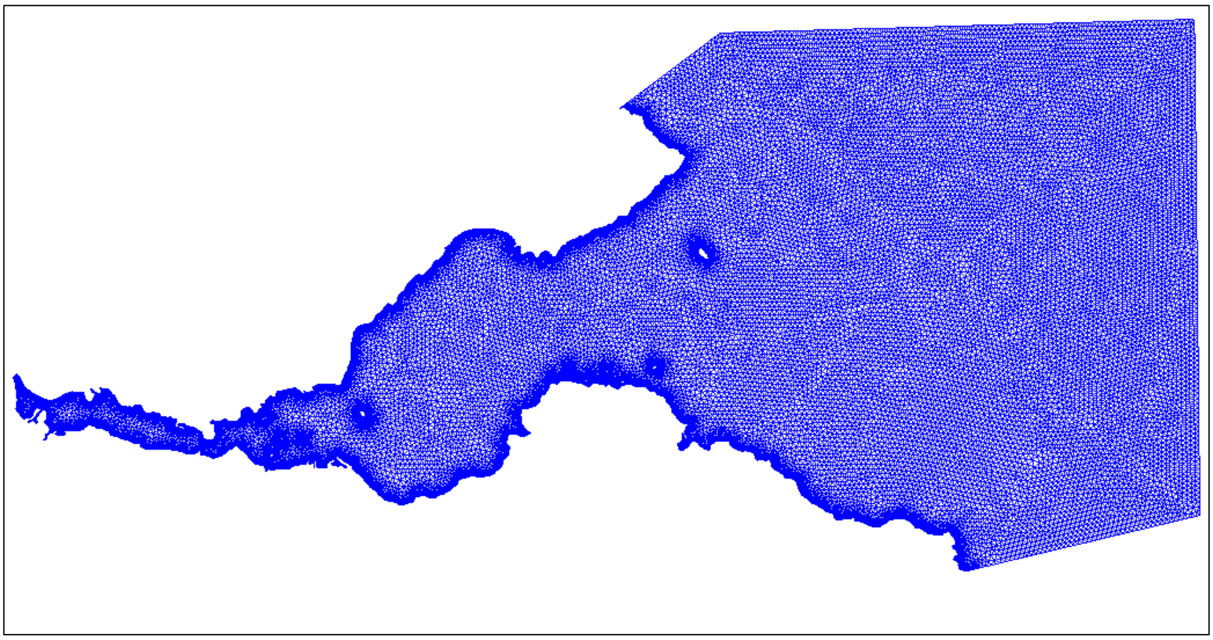

Figure 1 *Telemac 3D hydrodynamic mesh and model extent.*

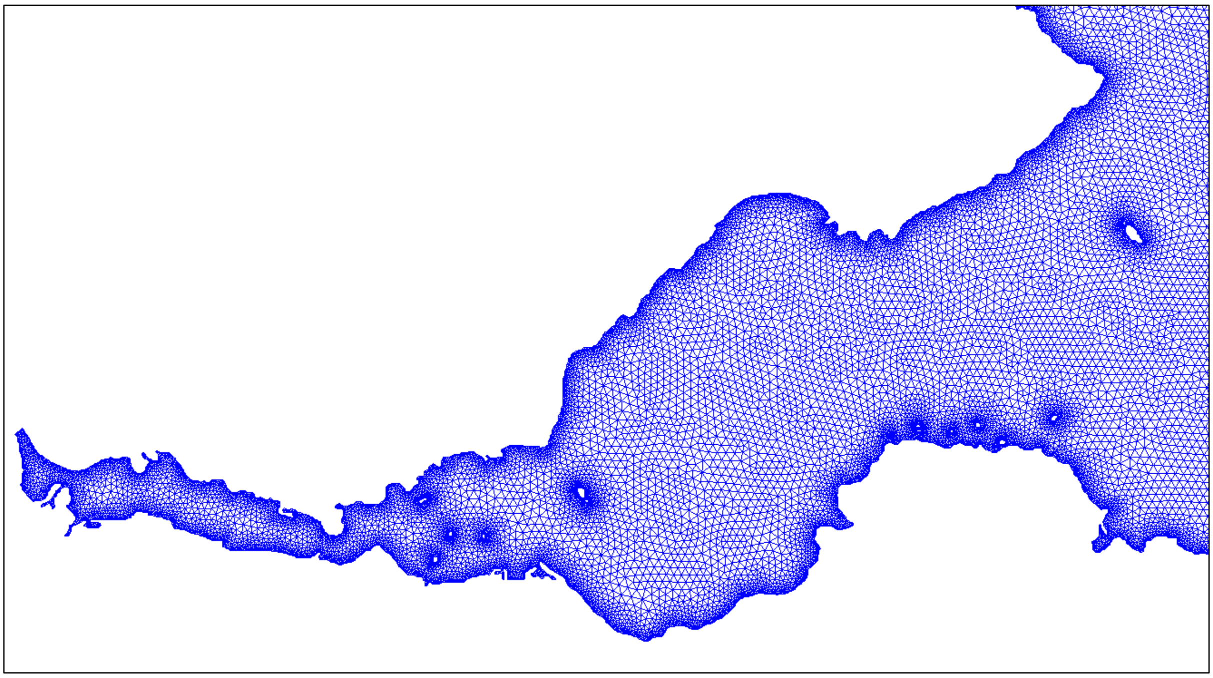

Figure 2 *Telemac 3D hydrodynamic mesh (zoomed).*

2.2 *Freshwater Inputs*

Figure 3 shows a map of freshwater discharge locations for the main rivers considered appropriate for the model. There were 16 river inflows and the average flowrates were extracted from the G2G dataset [G2G, 2018]. A salinity value of 0 PSU and temperature of 14 ^{o}C was employed as the inlet conditions.

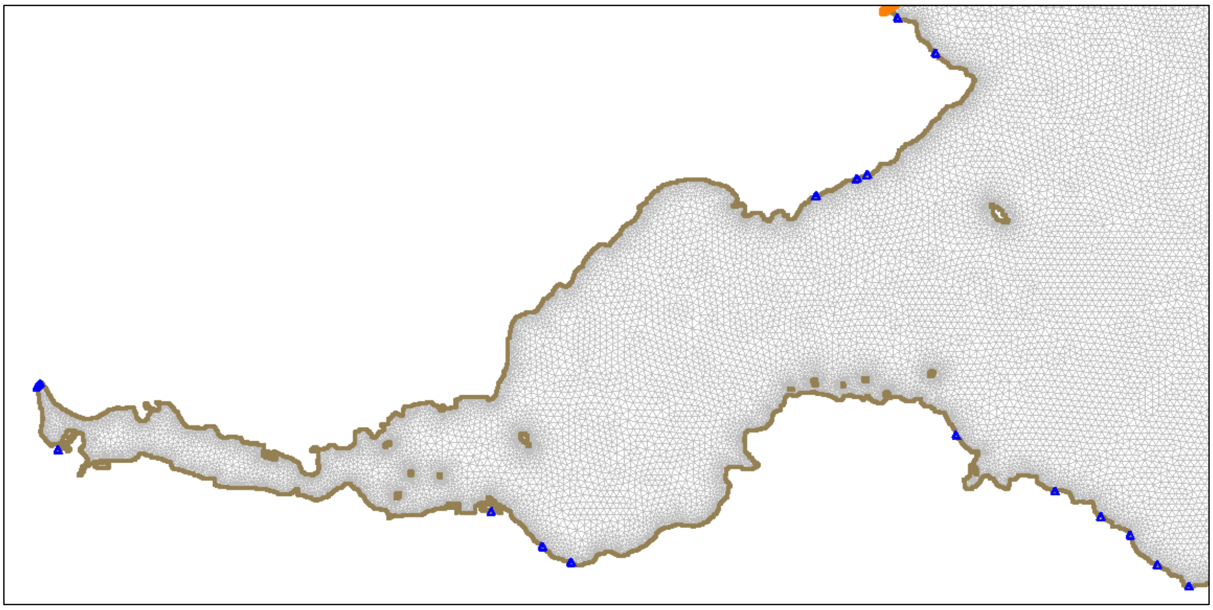

Figure 3 *The 16 river discharge locations shown as blue triangles.*

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. The bathymetry in the local area is shown in Figure 4.

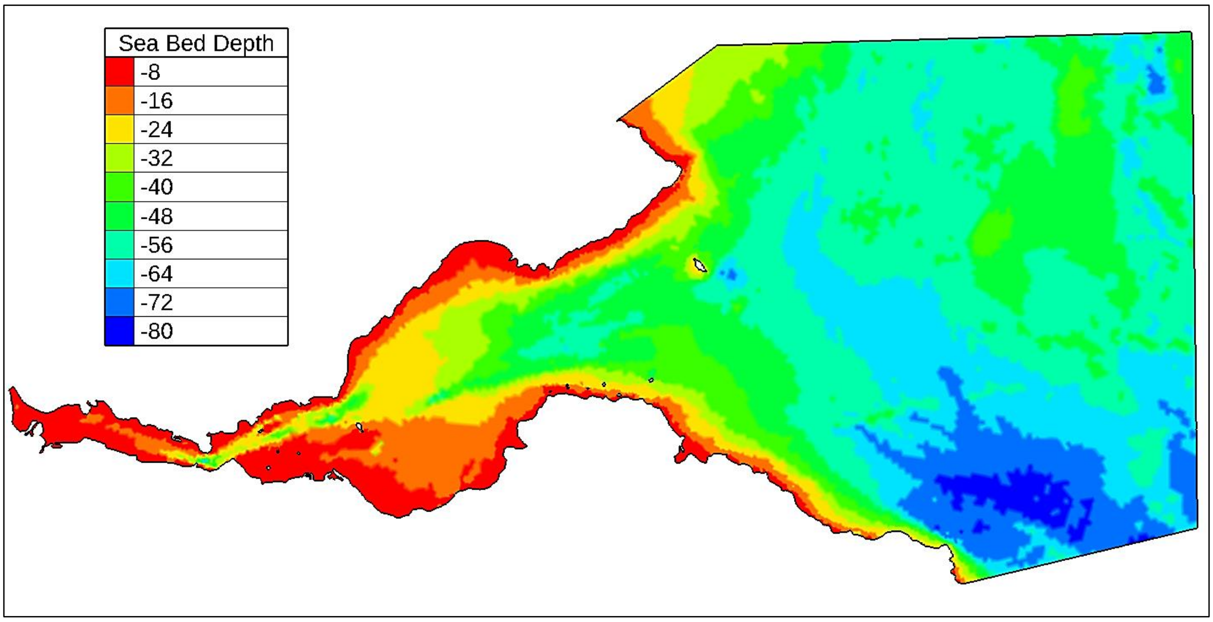

Figure 4 *Sea bed bathymetry in the Forth estuary area.*

2.3 *Meteorology*

Wind forcing on the estuary 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.

2.4 *Hydrodynamic runs*

The model was "spun-up" for 6 days (5th-11th August 2003) 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 time period 11th-29th August 2003.

Figures 4 and 5 show snapshots of the developed salinity and temperature fields, respectively.

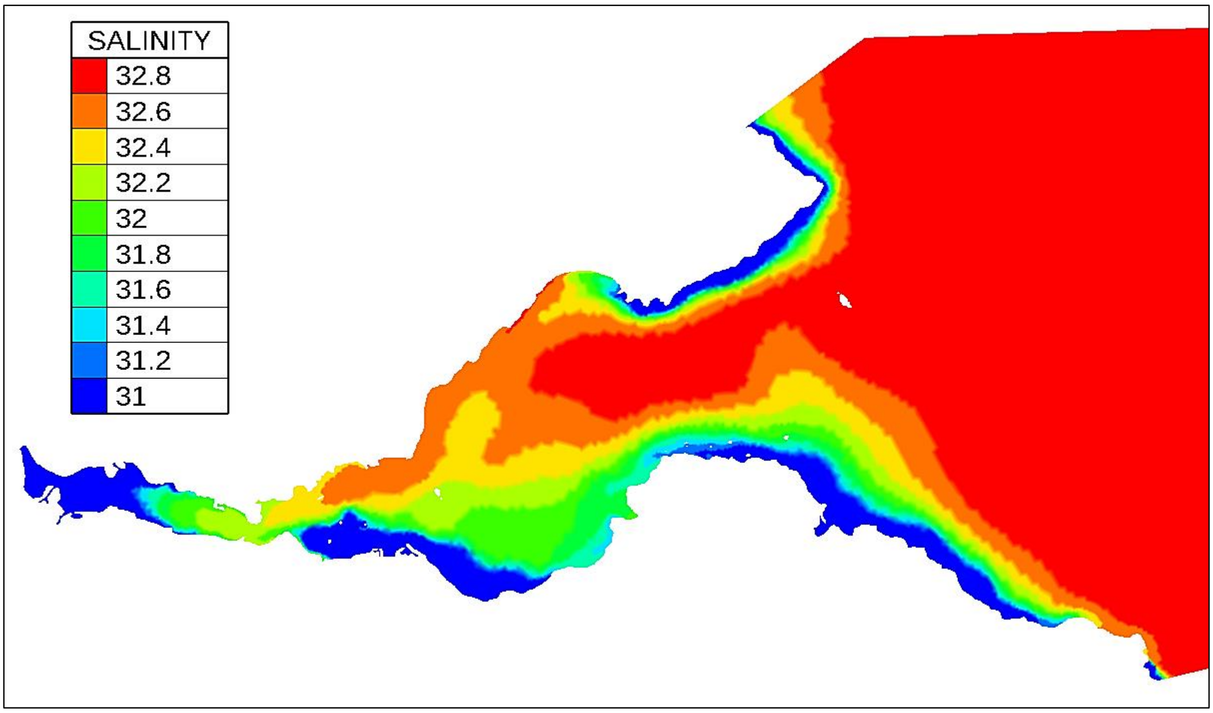

Figure 4 *Snapshot of near-surface salinity (PSU) on the 24th Aug 2003 at 7 a.m.*

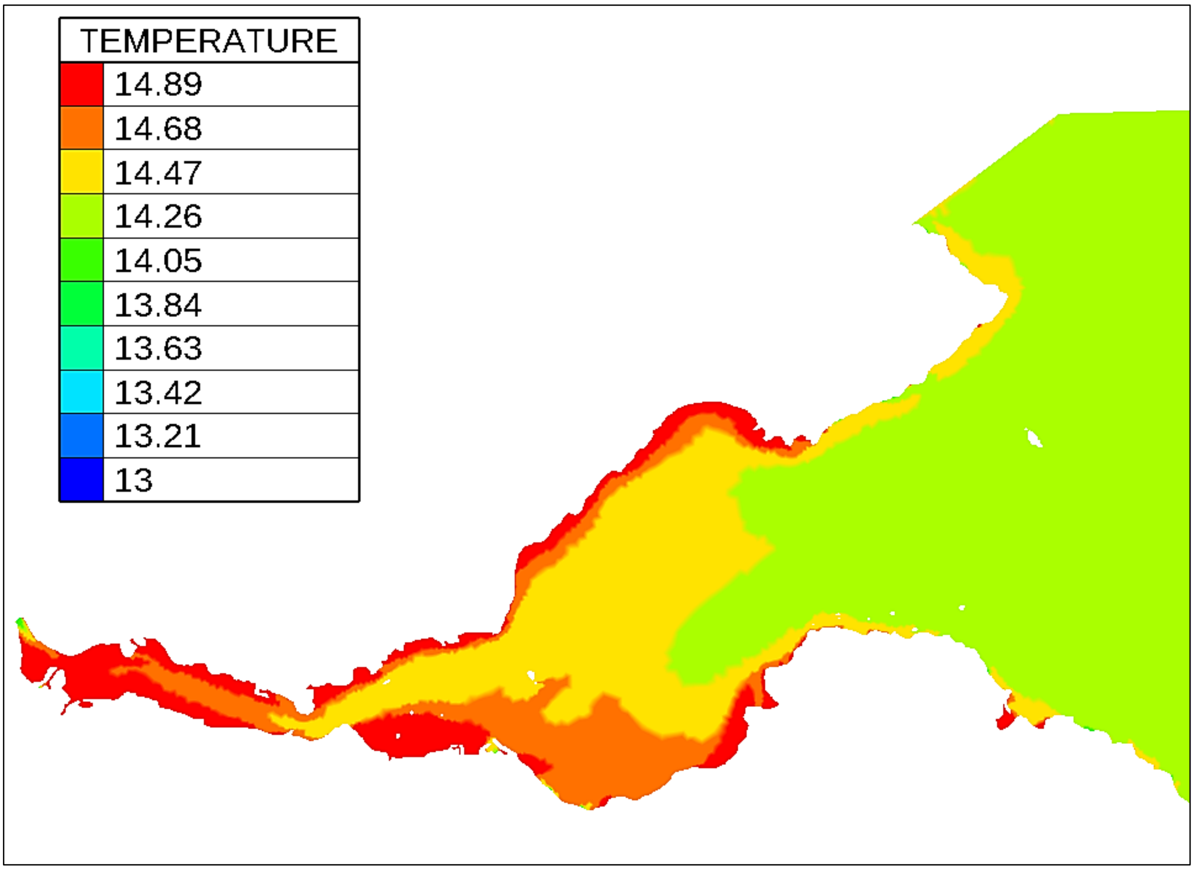

Figure 5 *Snapshot of near-surface temperature (^{o}C) on the 24th Aug 2003 at 7 a.m.*

2.5 *Flow fields*

Figures 6 and 7 show snapshots of typical near-surface flow patterns in the Firth of Forth on a flood and ebb tide, respectively, and highlight the complexity of the flows due to the competing effects of tides, wind and stratification.

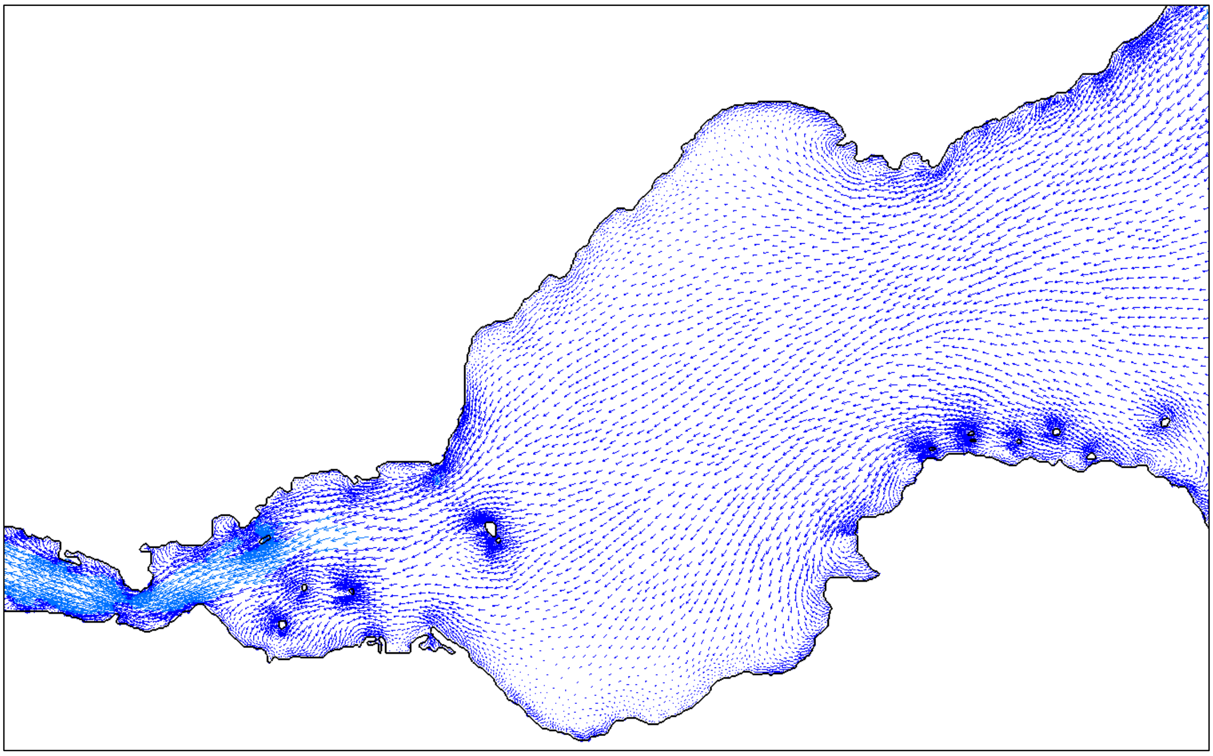

Figure 6 *Snapshot of surface flow patterns in the Forth Estuary on a flood tide.*

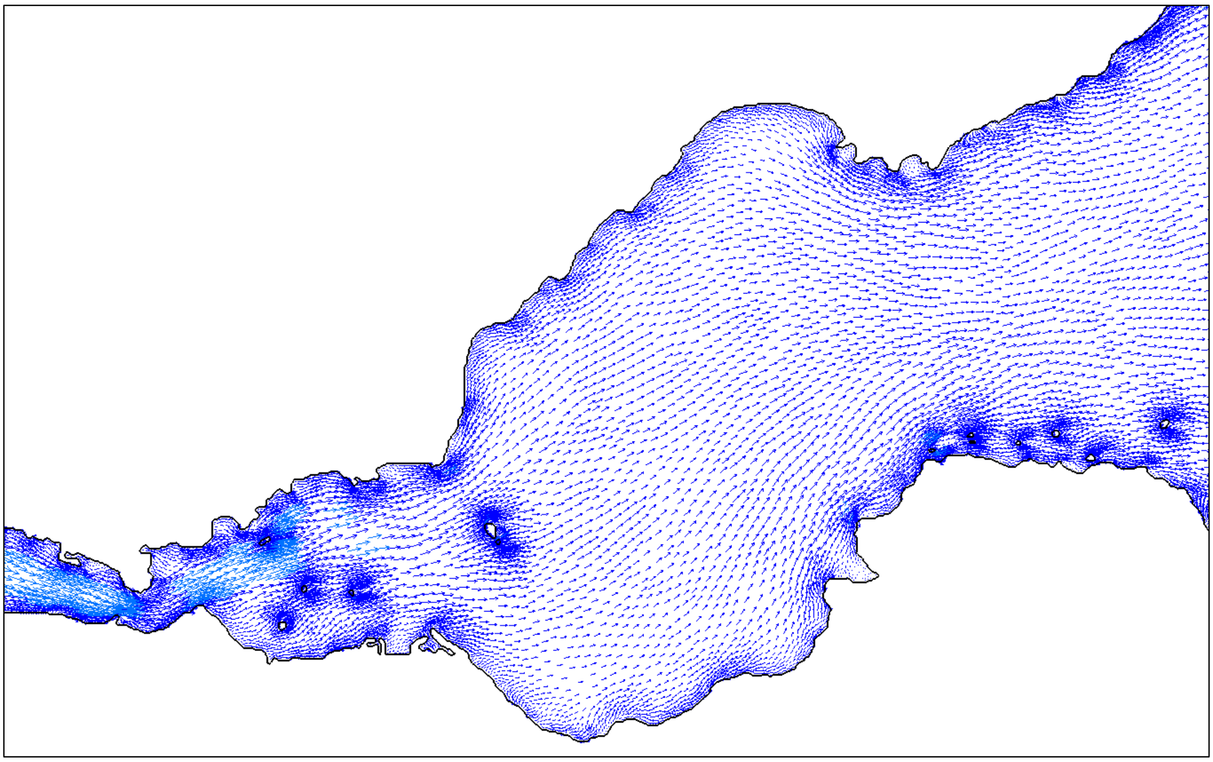

Figure 7 *Snapshot of surface flow patterns in the Forth Estuary on an ebb tide.*

2.6 *Site Locations for Model Validation*

5 sites were selected for the validation study with locations across the Forth system as shown in Fig.8

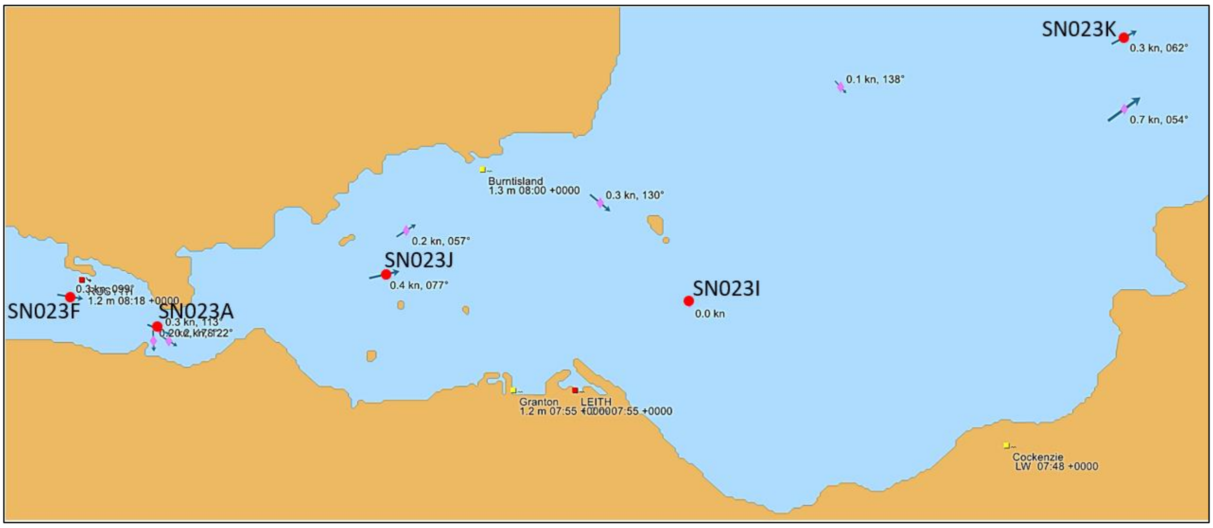

Figure 8 *Site locations for validation of the hydrodynamic model (red dots).*

At each of these 5 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. Its predictions are based on actual measurements over at least a 12-hour period at each site [FRC, 2009]. Table 1 gives further details of the site names and locations.

Table 1 *Site locations for model validation.*

Site Name	*Longitude (deg)*	*Latitude (deg)*
SN023K	-2.894266	56.104755
SN023I	-3.124733	56.016661
SN023J	-3.288633	56.019432
SN023A	-3.413333	56.002778
SN023F	-3.461274	56.014400

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 SN023K*

At the SN023K measurement location the sea surface height was satisfactorily modelled, with a perfect model skill score of 1.0 (Figure 9 and Table 2). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.1 m and 0.12 m, respectively, are about 2.0% and 2.4% 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 0.87 and 0.93, respectively. The values of the MAE and RMSE being in the range 6 – 12 cm s^{-1} (Table 2). Table 3 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 Telemac model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 10-13 demonstrate that the predicted currents were broadly of the same speed and direction as the ATT data.

Table 2. Model performance statistics for sea surface height (SSH), and East and North velocity at the measurement location SN023K between 11th- 29th August 2003.

	SSH	East	North
Skill, d2	1.0	0.93	0.87
Mean Absolute Error (MAE)	0.1 m	0.1 m/s	0.06 m/s
Root-Mean-Square Error (RMSE)	0.12 m	0.12 m/s	0.08 m/s

Table 3. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) and timing of high water at the measurement location SN023K between 11th- 29th August 2003.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	2.4 %	✓
SSH	+/- 15 % of Neap range (m)	6.6 %	✓
Timing of high water / phase	+/- 15 mins	9 mins	✓

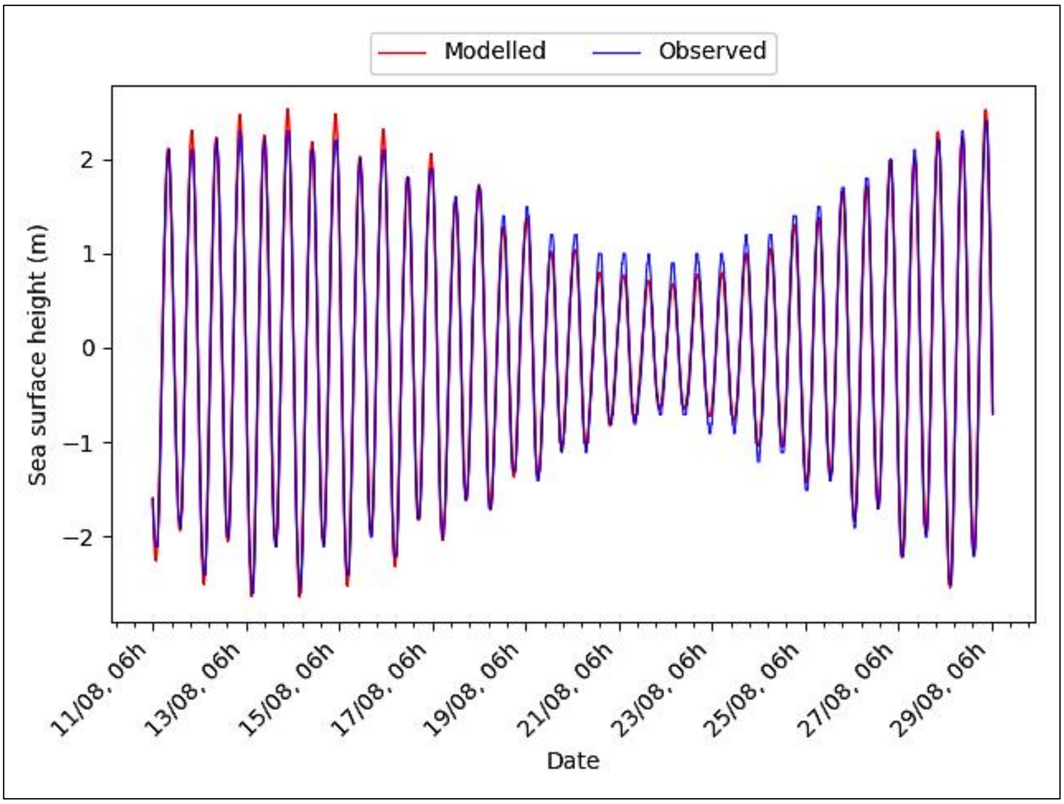

Figure 9 *Comparison between observed and modelled sea surface height from 11th- 29th August 2003 at measurement location SN023K. Model skill d2 = 1.0.*

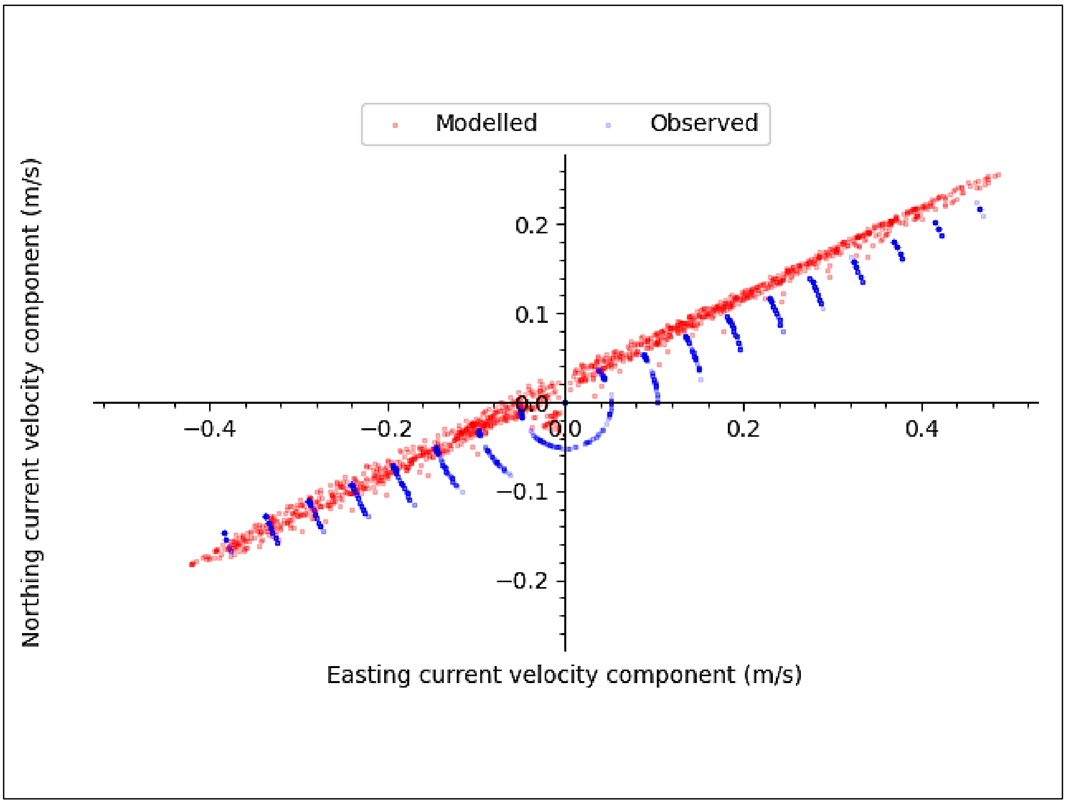

Figure 10 *Scatter plot of observed and modelled velocity from 11th- 29th August 2003 at measurement location SN023K.*

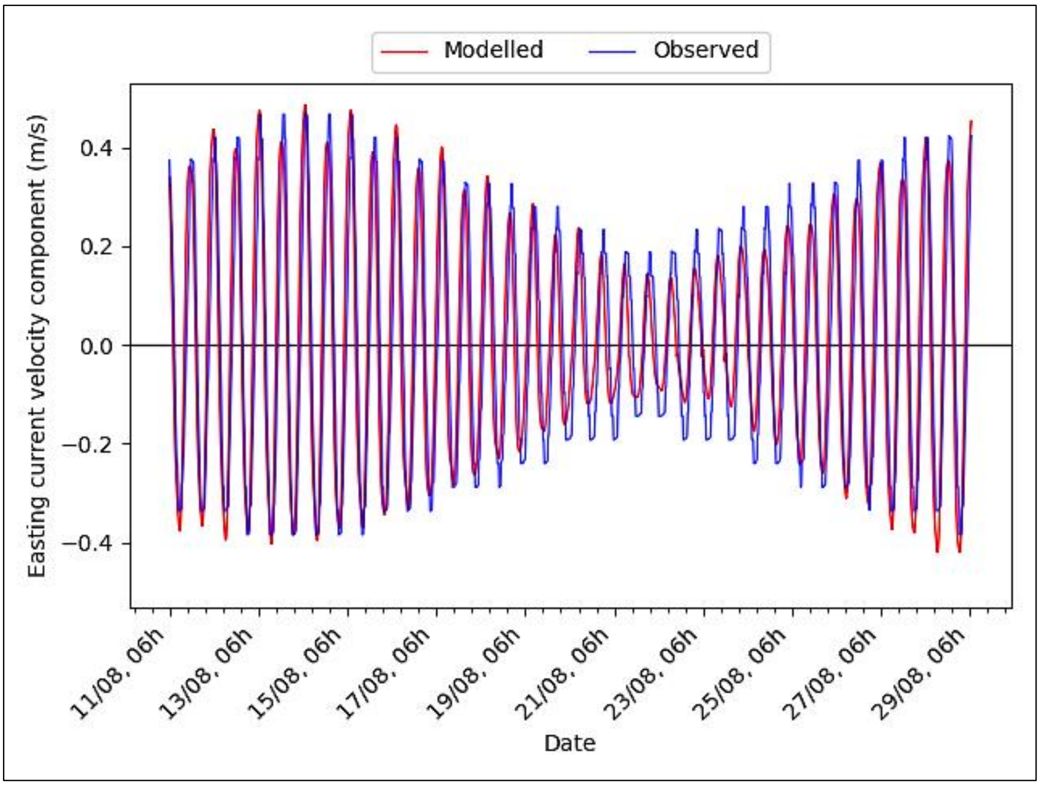

Figure 11 *Comparison between observed and modelled Easting velocity component from 11th- 29th August 2003 at measurement location SN023K. Model skill d2 = 0.93.*

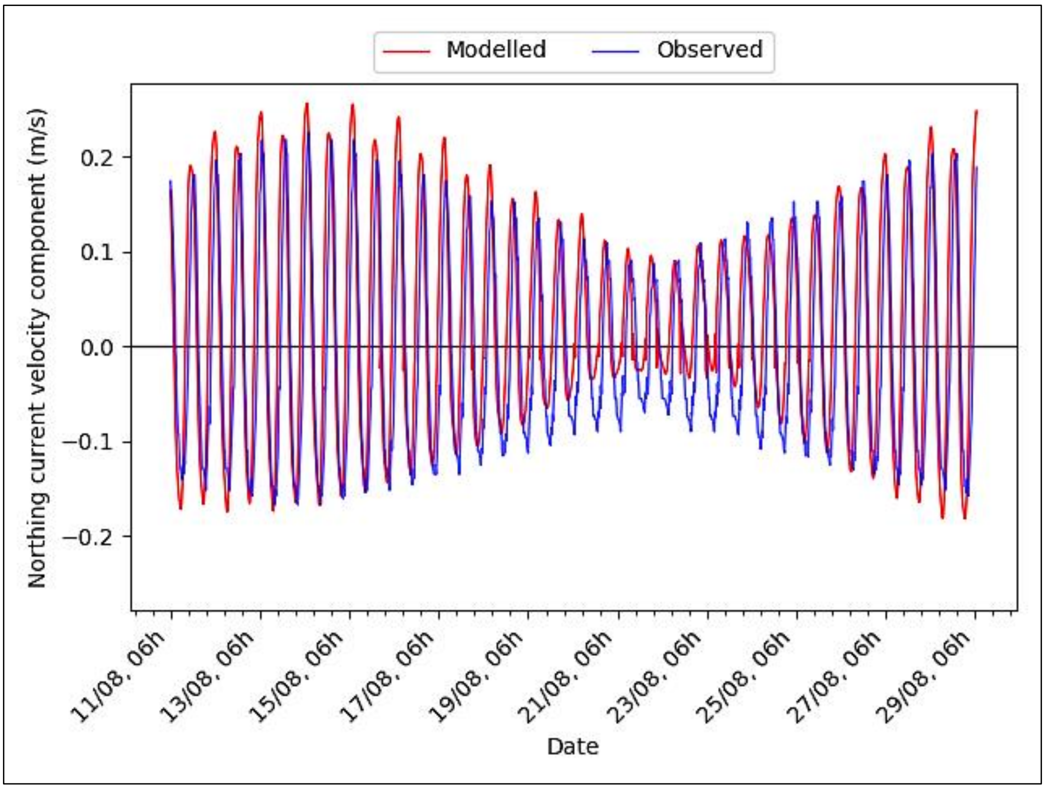

Figure 12 *Comparison between observed and modelled Northing velocity component from 11th- 29th August 2003 at measurement location SN023K. Model skill d2 = 0.87.*

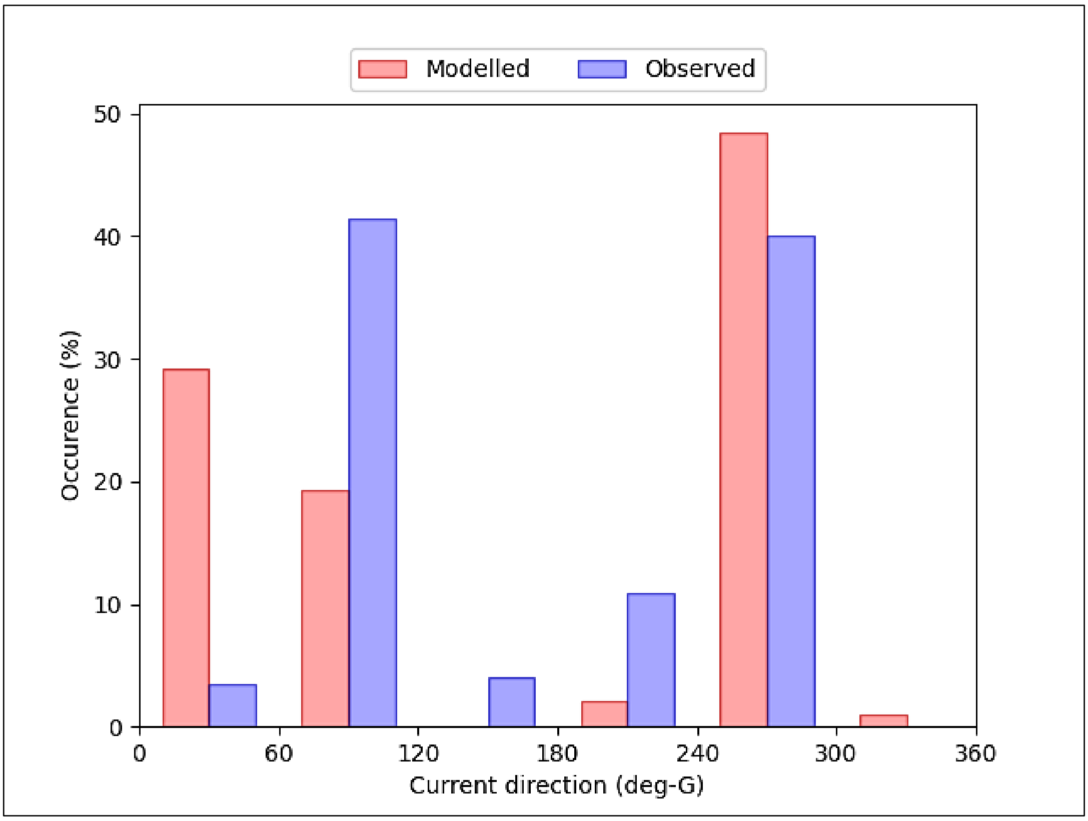

Figure 13 *Histogram of observed and modelled current direction from 11th- 29th August 2003 at measurement location SN023K. Model skill d2 = 0.81.*

3.2 *Site SN023I*

At the SN023I measurement location the sea surface height was satisfactorily modelled, with a perfect model skill score of 1.0 (Figure 14 and Table 4). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.12 m and 0.14 m, respectively, are about 2.4% and 2.8% 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 0.7 and 0.97, respectively. The values of the MAE and RMSE being in the range 3 – 7 cm s^{-1} (Table 4). Table 5 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 Telemac model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 15-18 demonstrate that the predicted currents were broadly of similar speed and direction compared with the ATT data.

Table 4. Model performance statistics for sea surface height (SSH), and East and North velocity at the measurement location SN023I between 11th- 29th August 2003.

	SSH	East	North
Skill, d2	1.0	0.97	0.7
Mean Absolute Error (MAE)	0.12 m	0.06 m/s	0.03 m/s
Root-Mean-Square Error (RMSE)	0.14 m	0.07 m/s	0.04 m/s

Table 5. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) and timing of high water at the measurement location SN023I between 11th- 29th August 2003.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	2.8 %	✓
SSH	+/- 15 % of Neap range (m)	7.7 %	✓
Timing of high water / phase	+/- 15 mins	9 mins	✓

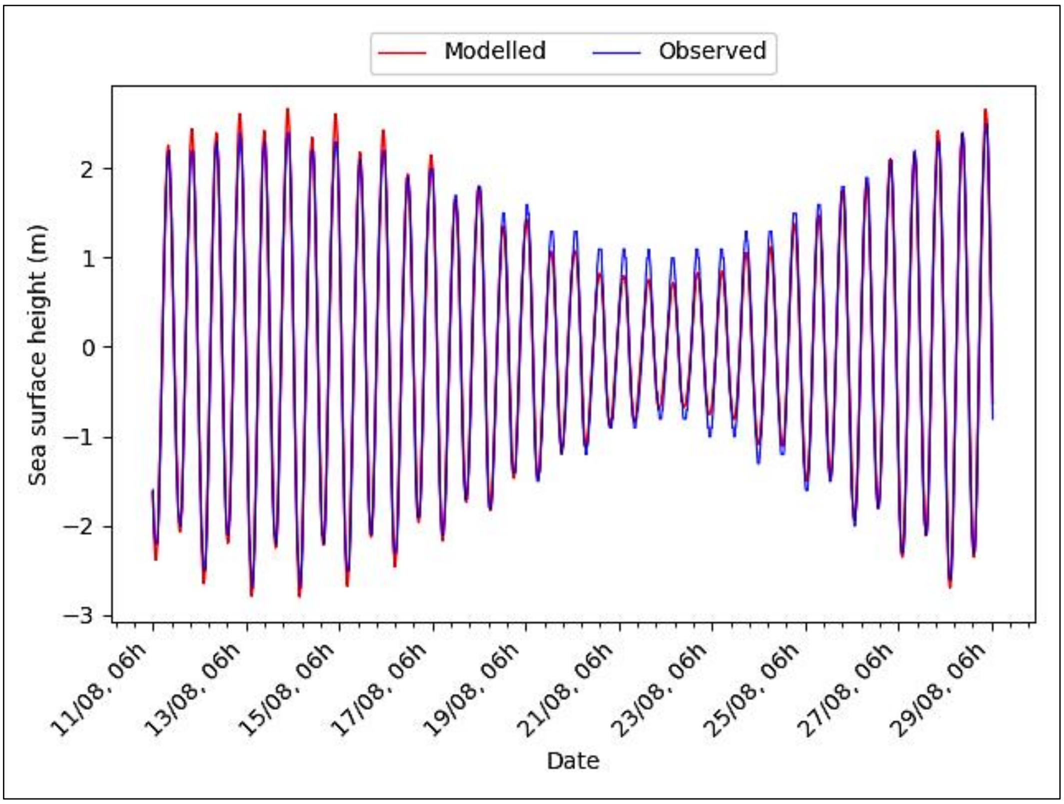

Figure 14 *Comparison between observed and modelled sea surface height from 11th- 29th August 2003 at measurement location SN023I. Model skill d2 = 1.0.*

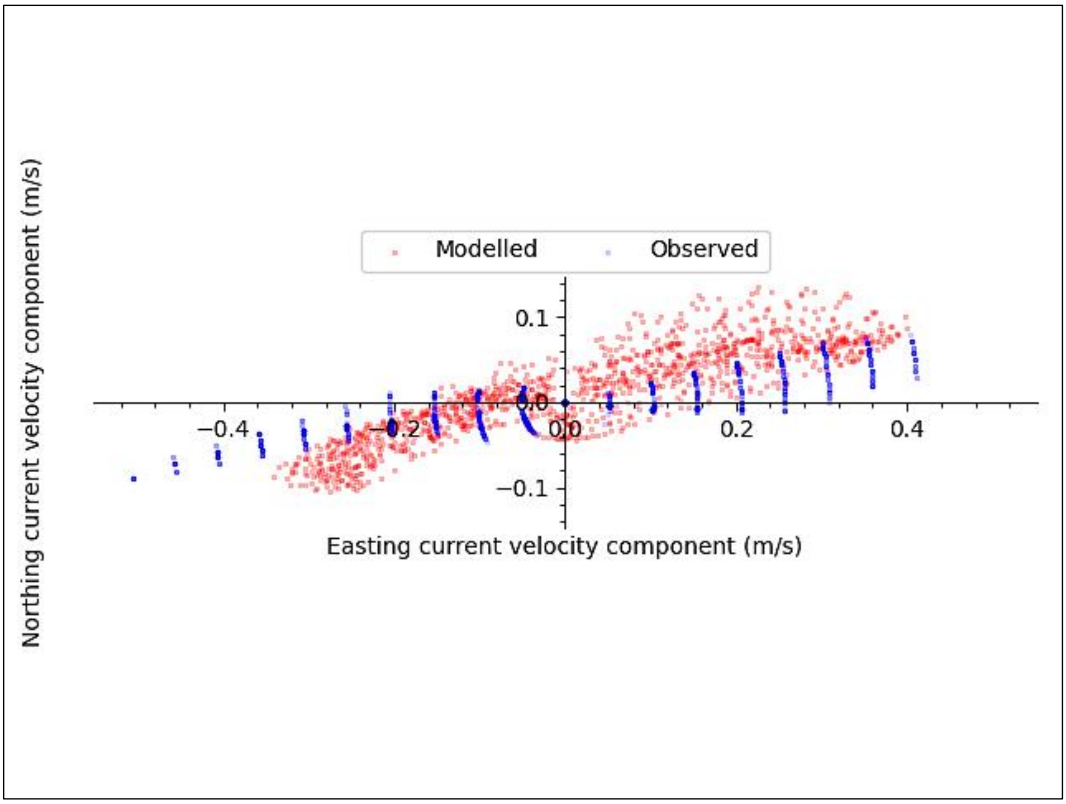

Figure 15 *Scatter plot of observed and modelled velocity from 11th- 29th August 2003 at measurement location SN023I.*

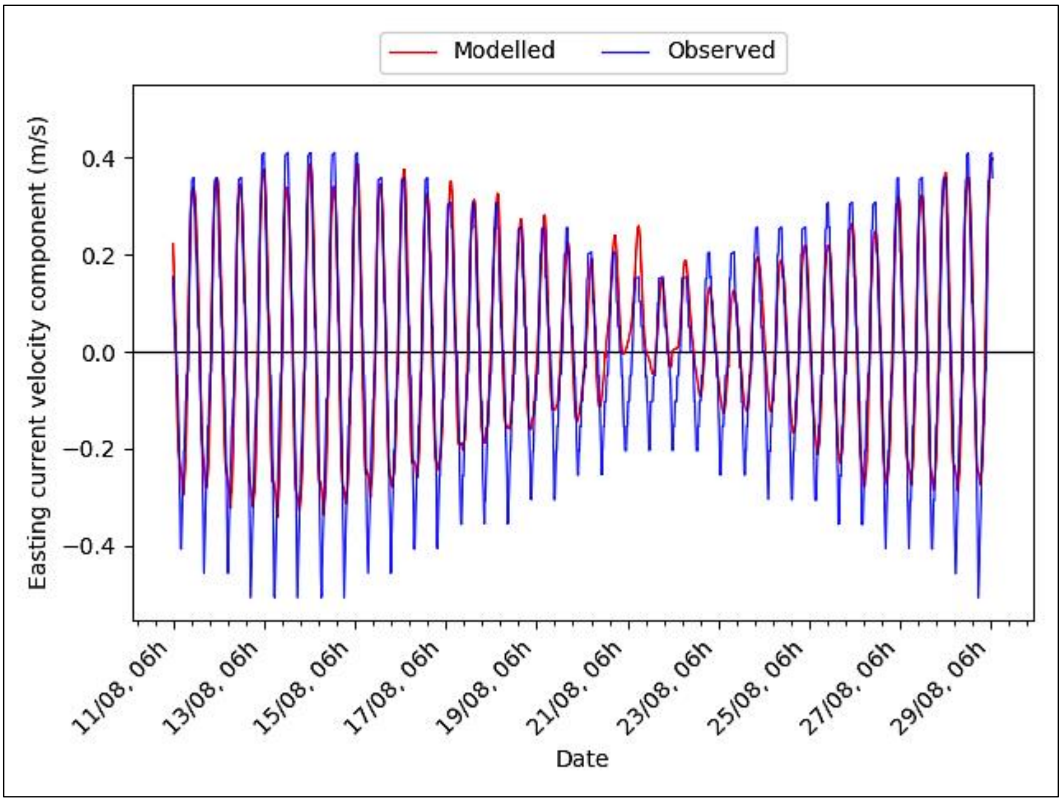

Figure 16 *Comparison between observed and modelled Easting velocity component from 11th- 29th August 2003 at measurement location SN023I. Model skill d2 = 0.97.*

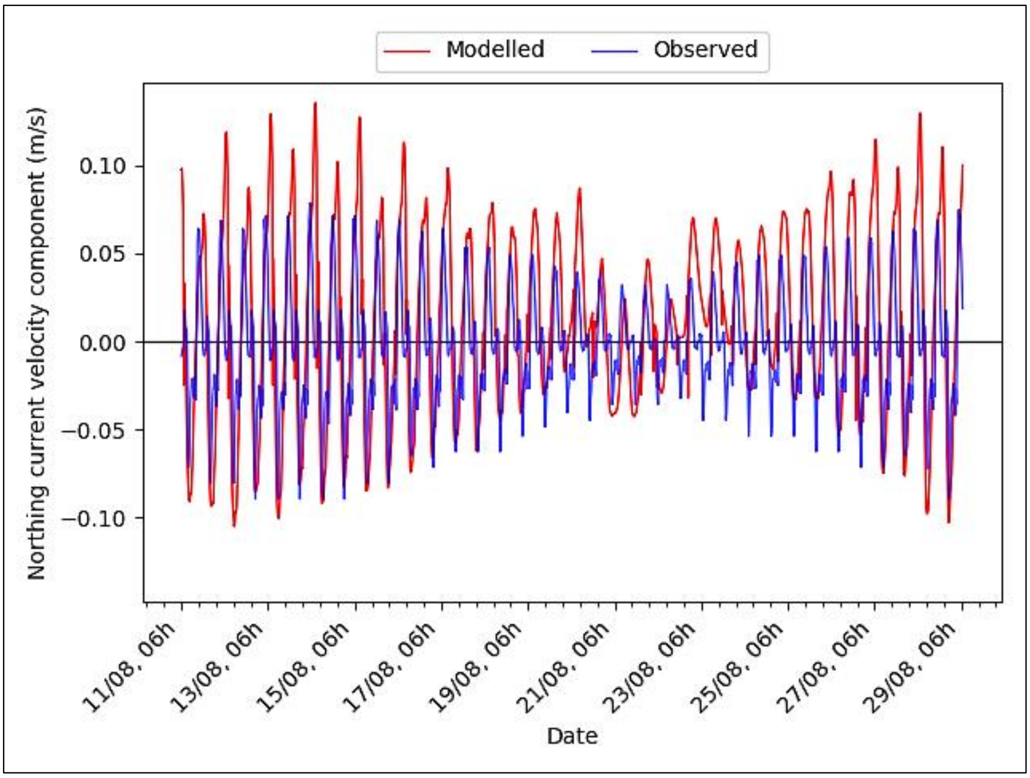

Figure 17 *Comparison between observed and modelled Northing velocity component from 11th- 29th August 2003 at measurement location SN023I. Model skill d2 = 0.7.*

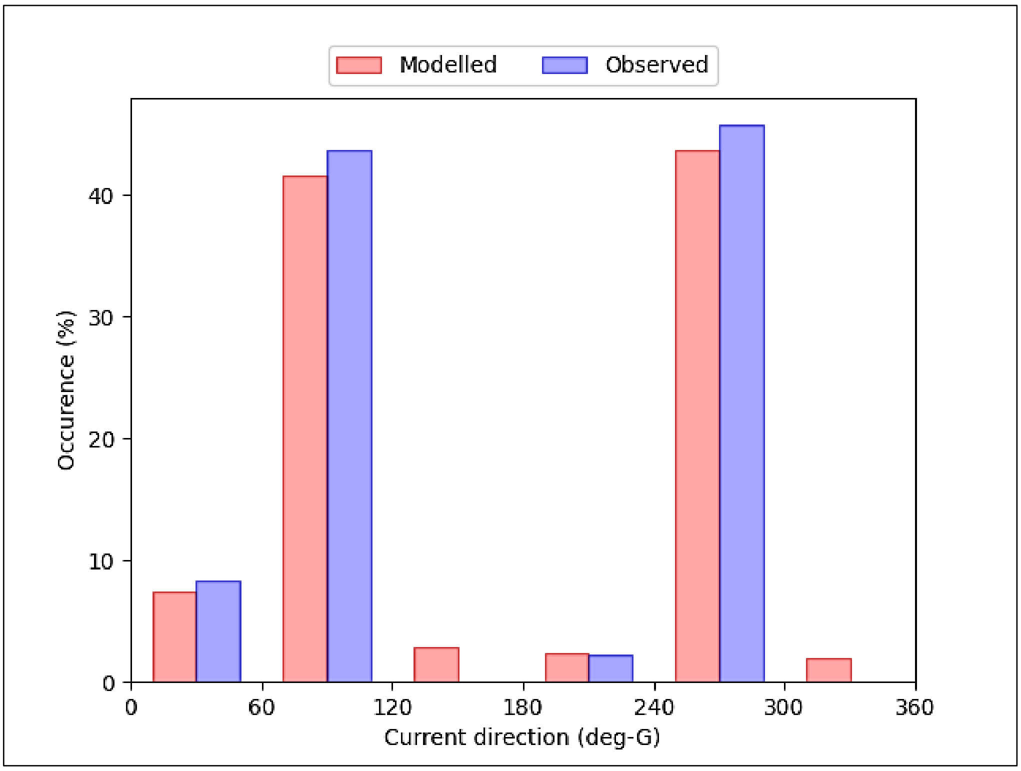

Figure 18 *Histogram of observed and modelled current direction from 11th- 29th August 2003 at measurement location SN023I. Model skill d2 = 1.0.*

3.3 *Site SN023J*

At the SN023J measurement location the sea surface height was satisfactorily modelled, with a perfect model skill score of 1.0 (Figure 19 and Table 6). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.12 m and 0.14 m, respectively, are about 2.4% and 2.8% 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 0.85 and 0.83, respectively. The values of the MAE and RMSE being in the range 6 – 24 cm s^{-1} (Table 6). Table 7 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 Telemac model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 20-23 demonstrate that the predicted currents were broadly of similar speed and direction compared with the ATT data.

Table 6. Model performance statistics for sea surface height (SSH), and East and North velocity at the measurement location SN023J between 11^{th}- 29^{th} August 2003.

	SSH	**East**	**North**
Skill, d2	1.0	0.83	0.85
Mean Absolute Error (MAE)	0.12 m	0.19 m/s	0.05 m/s
Root-Mean-Square Error (RMSE)	0.14 m	0.24 m/s	0.06 m/s

Table 7. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) and timing of high water at the measurement location SN023J between 11^{th}- 29^{th} August 2003.

	SEPA Standard	**Telemac3D**	**Result**
SSH	+/- 10 % of Spring range (m)	2.8 %	✓
SSH	+/- 15 % of Neap range (m)	7.7 %	✓
Timing of high water / phase	+/- 15 mins	8 mins	✓

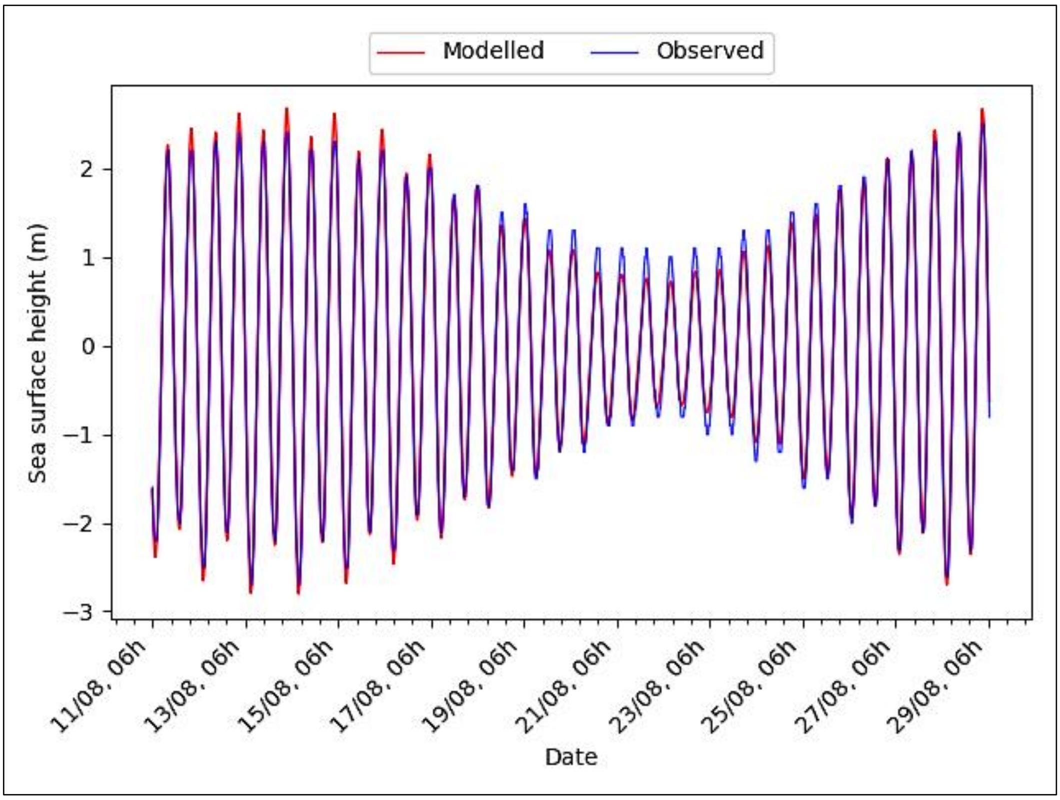

Figure 19 *Comparison between observed and modelled sea surface height from 11th- 29th August 2003 at measurement location SN023J. Model skill d2 = 1.0.*

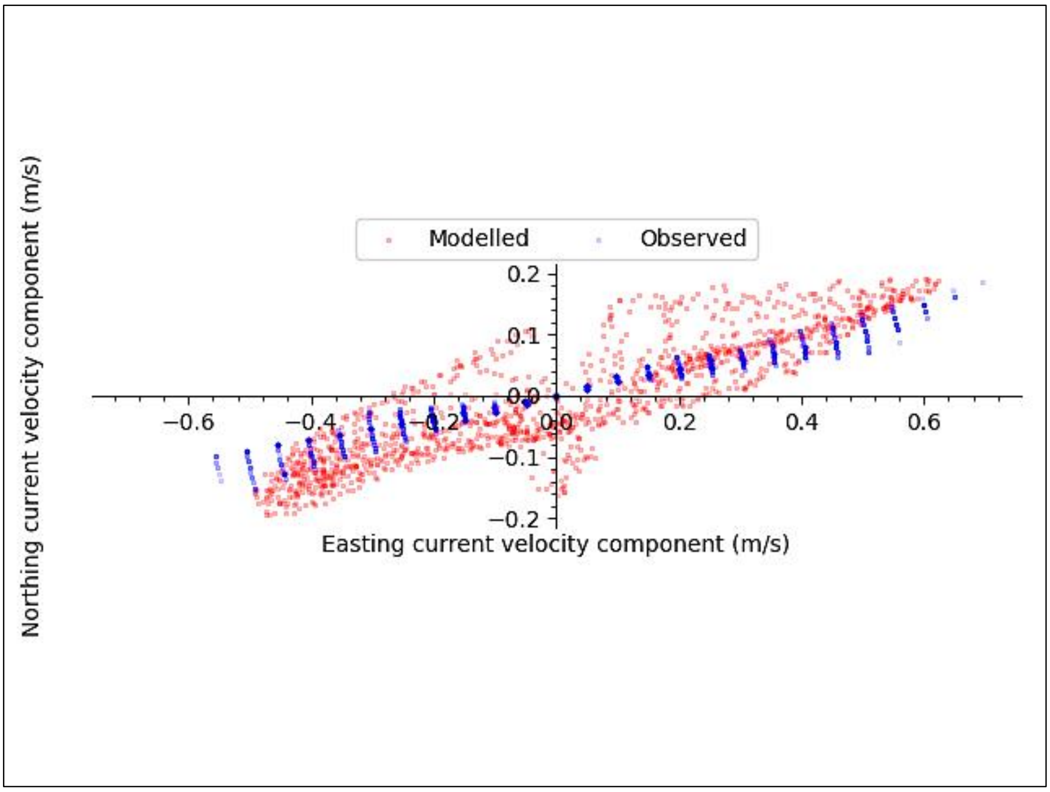

Figure 20 *Scatter plot of observed and modelled velocity from 11th- 29th August 2003 at measurement location SN023J.*

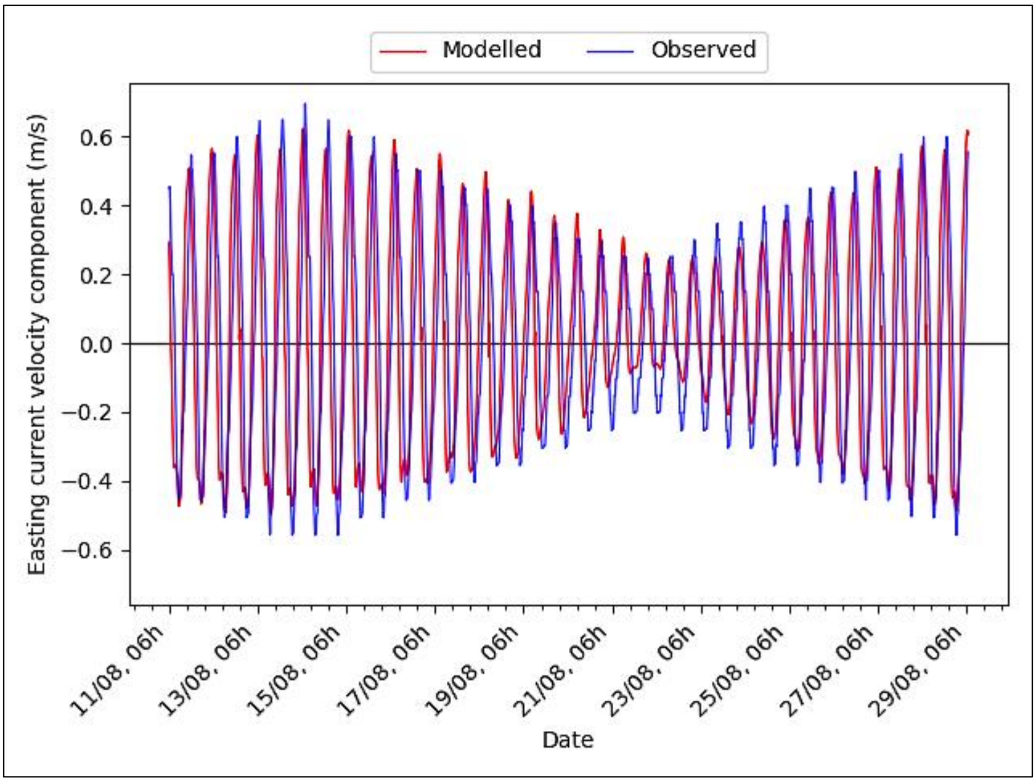

Figure 21 *Comparison between observed and modelled Easting velocity component from 11th- 29th August 2003 at measurement location SN023J. Model skill d2 = 0.83.*

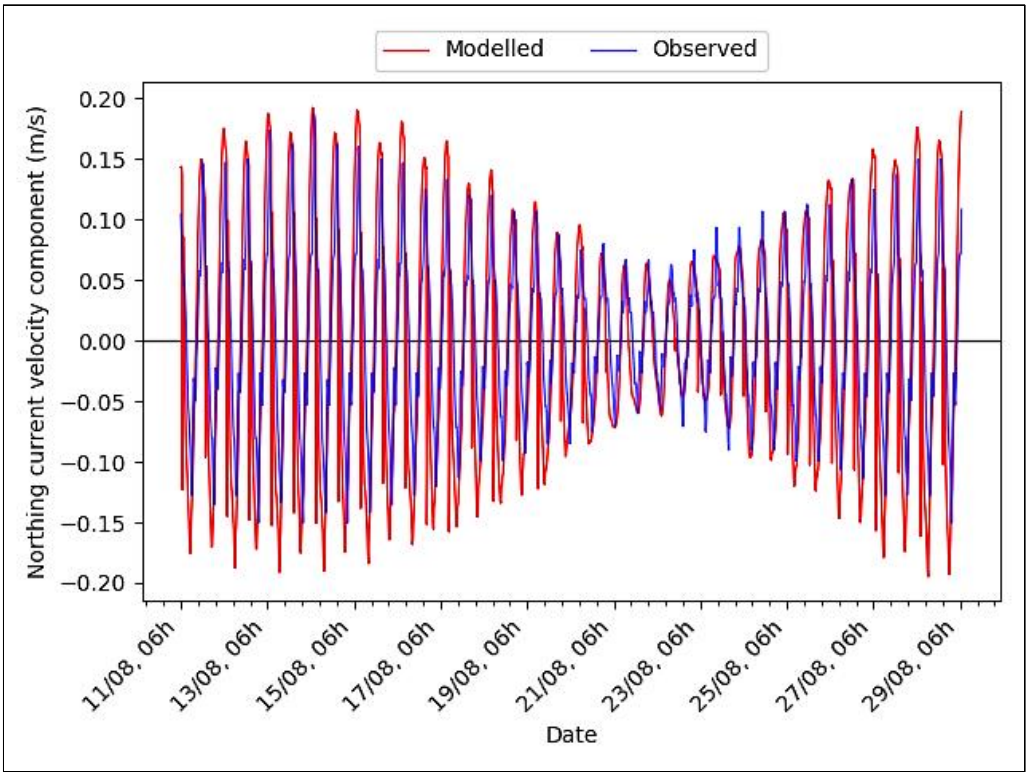

Figure 22 *Comparison between observed and modelled Northing velocity component from 11th- 29th August 2003 at measurement location SN023J. Model skill d2 = 0.85.*

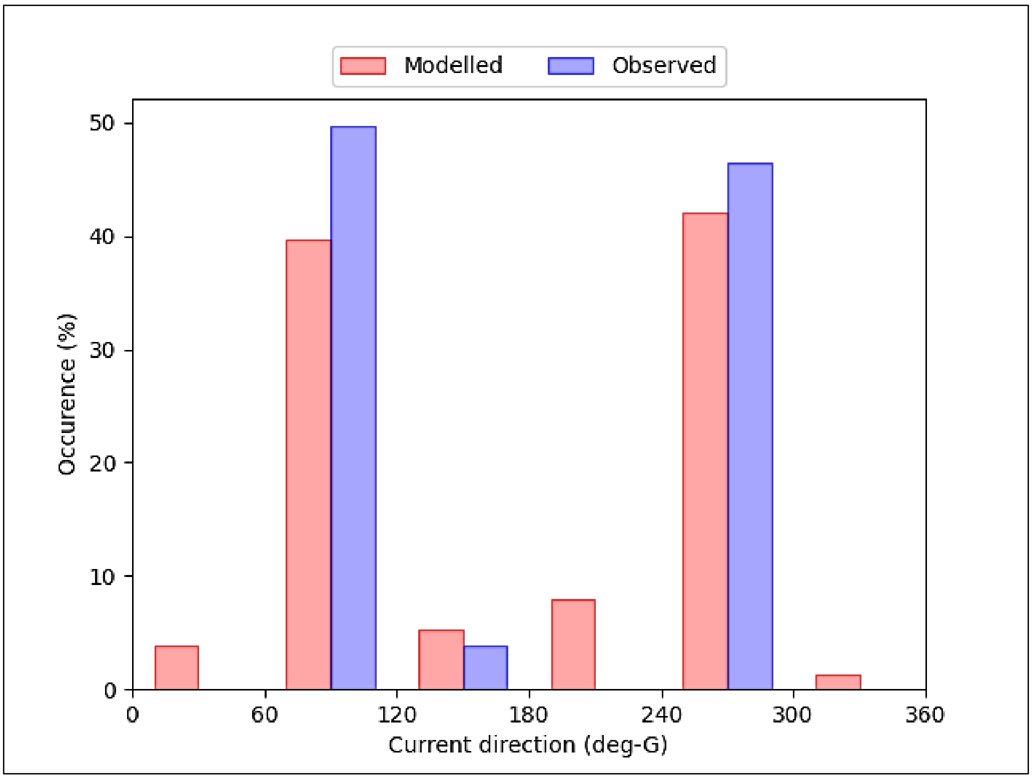

Figure 23 *Histogram of observed and modelled current direction from 11th- 29th August 2003 at measurement location SN023J. Model skill d2 = 0.98.*

3.4 *Site SN023A*

At the SN023A measurement location the sea surface height was satisfactorily modelled, with a model skill score of 0.99 (Figure 24 and Table 8). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.17 m and 0.2 m, respectively, are about 3.4% and 4.0% 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 0.92 and 0.94, respectively. The values of the MAE and RMSE being in the range 5 – 20 cm s^{-1} (Table 8). Table 9 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 Telemac model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 25-28 demonstrate that the predicted currents were broadly of similar speed and direction compared with the ATT data.

Table 8. Model performance statistics for sea surface height (SSH), and East and North velocity at the measurement location SN023A between 11th- 29th August 2003.

	SSH	East	North
Skill, d2	0.99	0.94	0.92
Mean Absolute Error (MAE)	0.17 m	0.16 m/s	0.05 m/s
Root-Mean-Square Error (RMSE)	0.2 m	0.2 m/s	0.06 m/s

Table 9. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) and timing of high water at the measurement location SN023A between 11th- 29th August 2003.

	SEPA Standard	**Telemac3D**	**Result**
SSH	+/- 10 % of Spring range (m)	4.0 %	✓
SSH	+/- 15 % of Neap range (m)	11.1 %	✓
Timing of high water / phase	+/- 15 mins	9 mins	✓

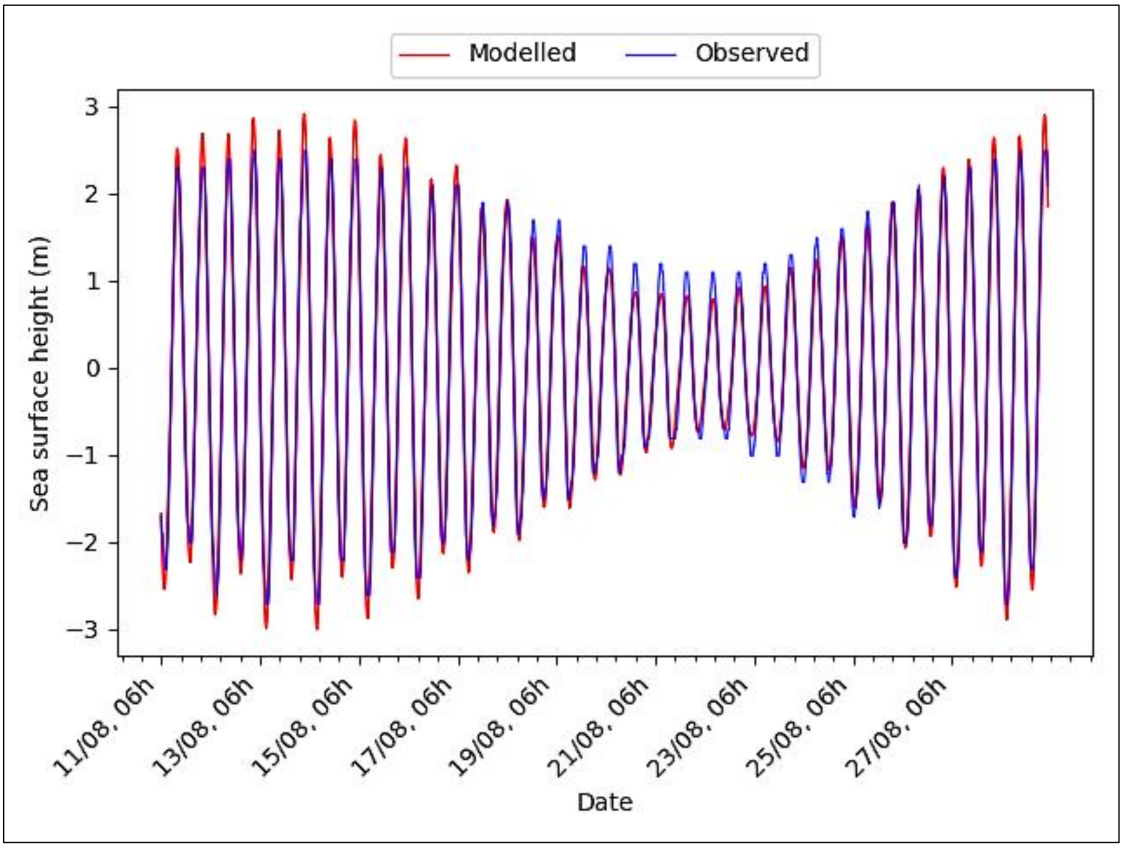

Figure 24 *Comparison between observed and modelled sea surface height from 11th- 29th August 2003 at measurement location SN023A. Model skill d2 = 0.99.*

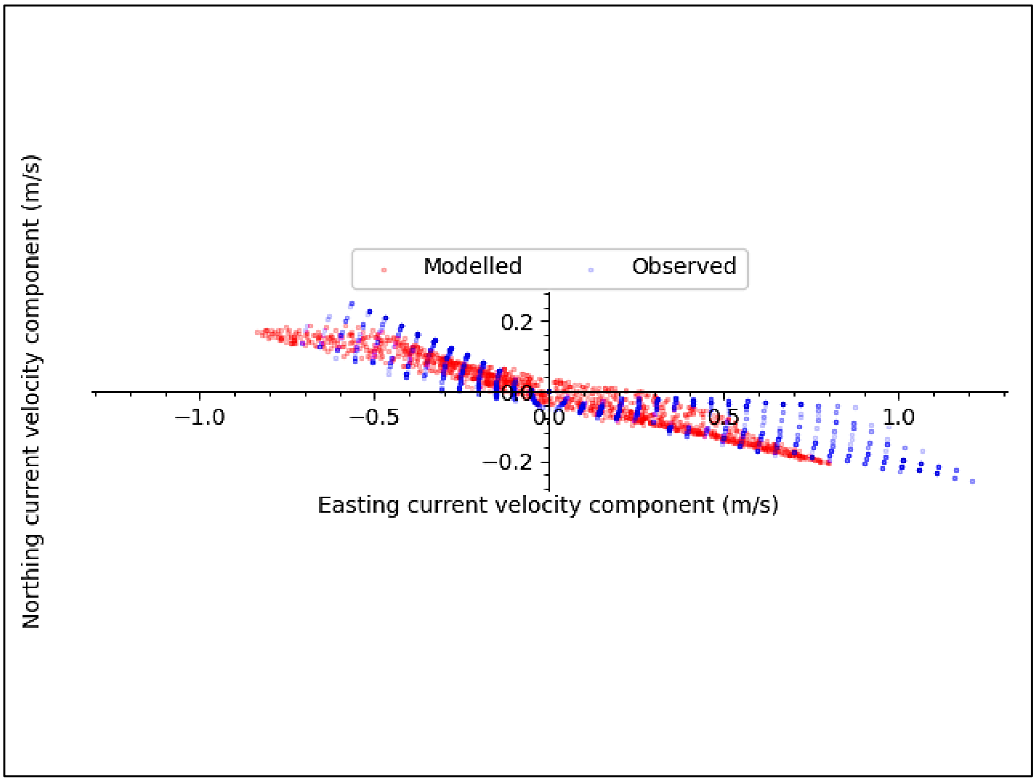

Figure 25 *Scatter plot of observed and modelled velocity from 11th- 29th August 2003 at measurement location SN023A.*

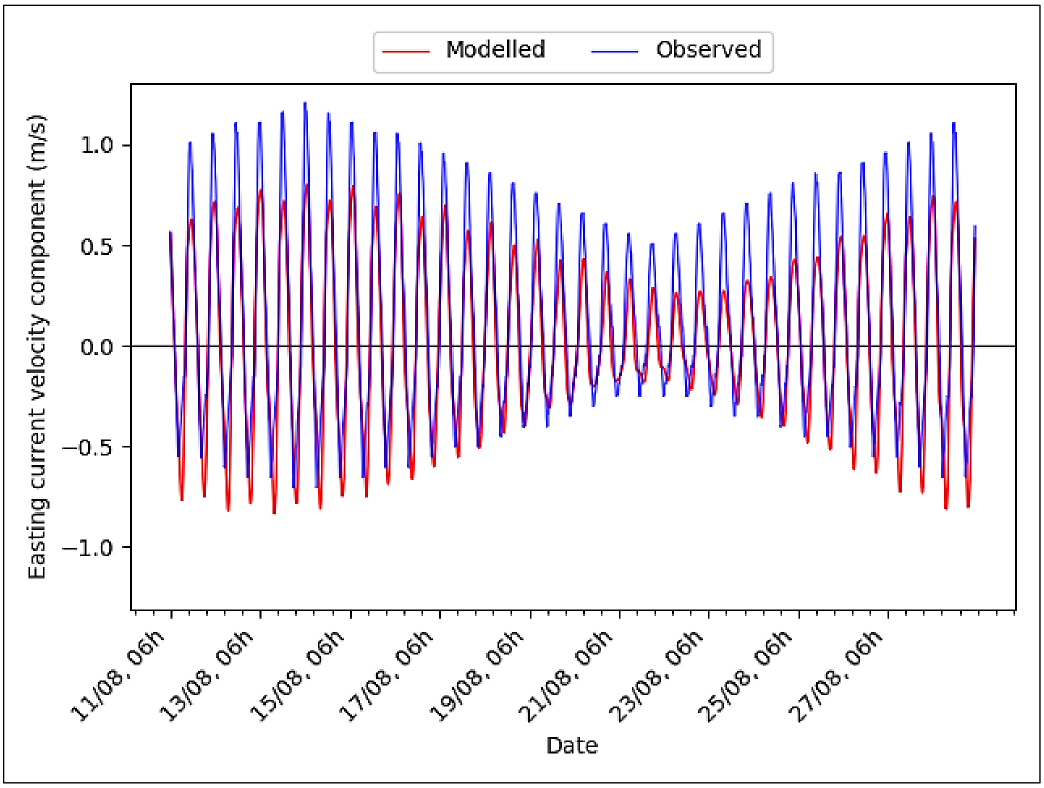

Figure 26 *Comparison between observed and modelled Easting velocity component from 11th- 29th August 2003 at measurement location SN023A. Model skill d2 = 0.94.*

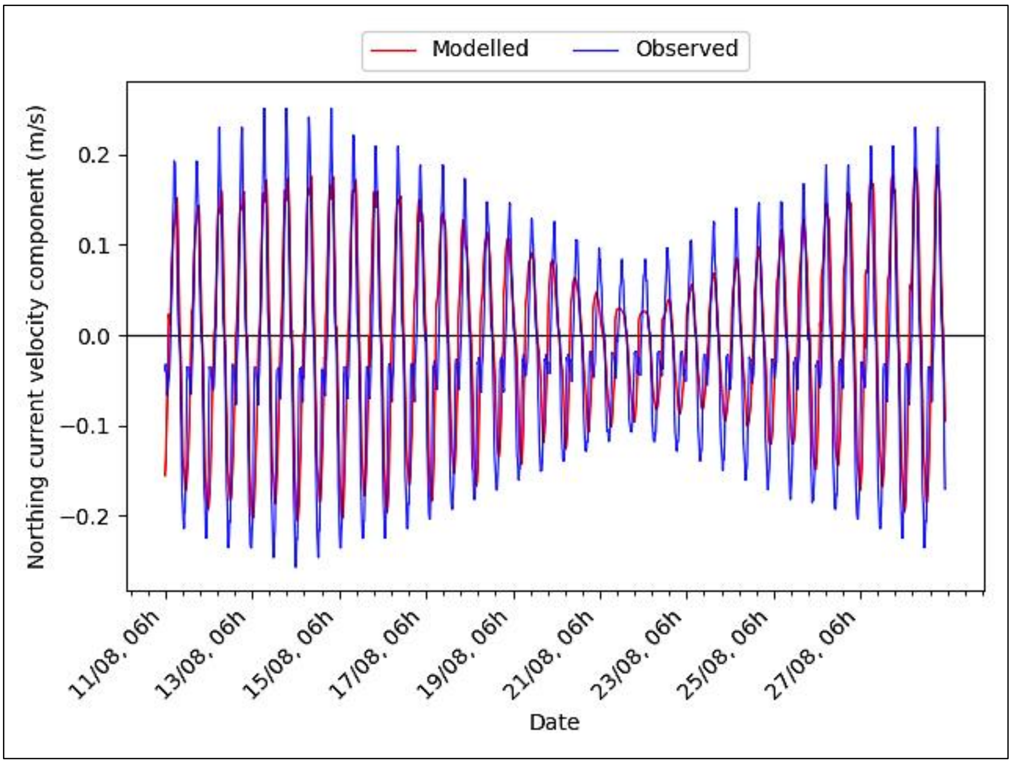

Figure 27 *Comparison between observed and modelled Northing velocity component from 11th- 29th August 2003 at measurement location SN023A. Model skill d2 = 0.92.*

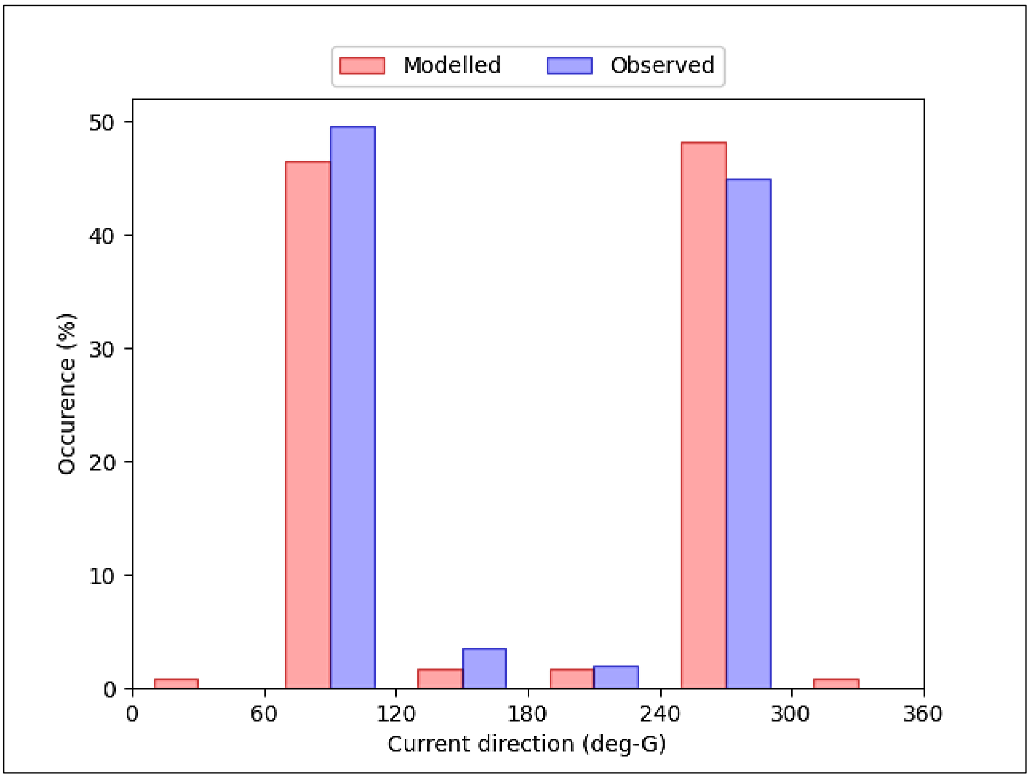

Figure 28 *Histogram of observed and modelled current direction from 11th- 29th August 2003 at measurement location SN023A. Model skill d2 = 1.0.*

3.5 *Site SN023F*

At the SN023F measurement location the sea surface height was satisfactorily modelled, with a model skill score of 0.99 (Figure 29 and Table 10). The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.17 m and 0.2 m, respectively, are about 3.4% and 4.0% 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 0.96 and 0.95, respectively. The values of the MAE and RMSE being in the range 8 – 21 cm s^{-1} (Table 10). Table 11 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 Telemac model data are in satisfactory agreement with the SEPA standards. The scatter plots and histograms shown in Figures 30-33 demonstrate that the predicted currents were broadly of similar speed and direction compared with the ATT data.

Table 10. Model performance statistics for sea surface height (SSH), and East and North velocity at the measurement location SN023F between 11th- 29th August 2003.

	SSH	East	North
Skill, d2	0.99	0.95	0.96
Mean Absolute Error (MAE)	0.17 m	0.17 m/s	0.08 m/s
Root-Mean-Square Error (RMSE)	0.20 m	0.21 m/s	0.09 m/s

Table 11. Model performance against SEPA standards [SEPA, 2019] for sea surface height (SSH) and timing of high water at the measurement location SN023F between 11th- 29th August 2003.

	SEPA Standard	Telemac3D	Result
SSH	+/- 10 % of Spring range (m)	4.0 %	✓
SSH	+/- 15 % of Neap range (m)	11.1 %	✓
Timing of high water / phase	+/- 15 mins	9 mins	✓

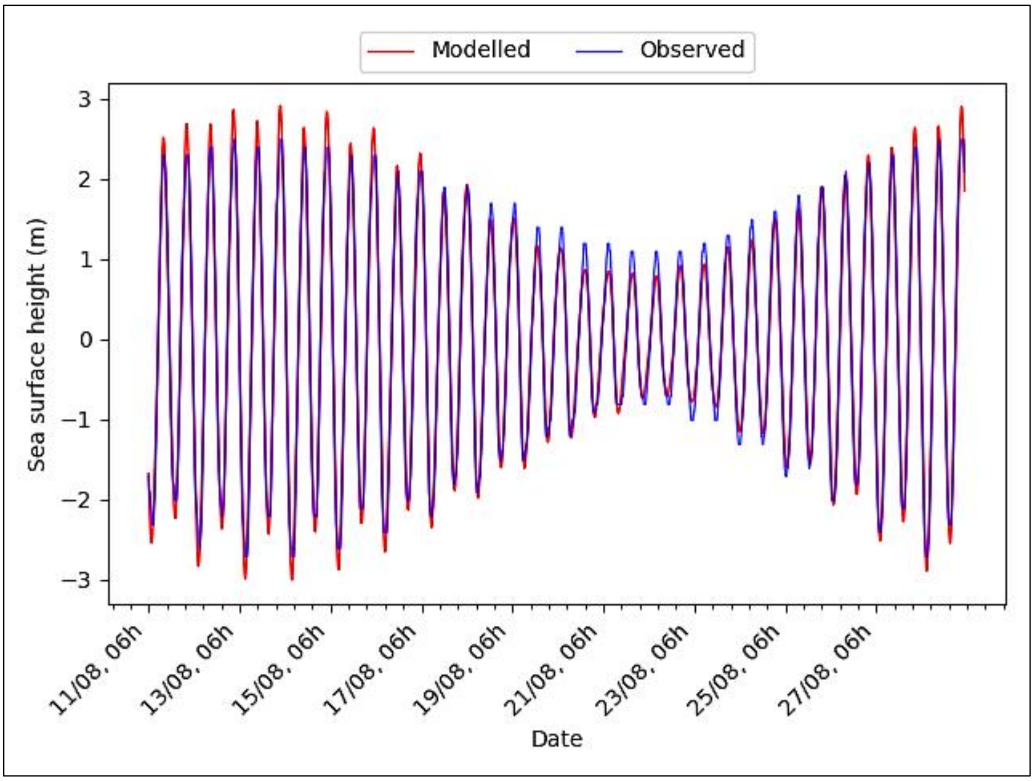

Figure 29 *Comparison between observed and modelled sea surface height from 11th- 29th August 2003 at measurement location SN023F. Model skill d2 = 0.99.*

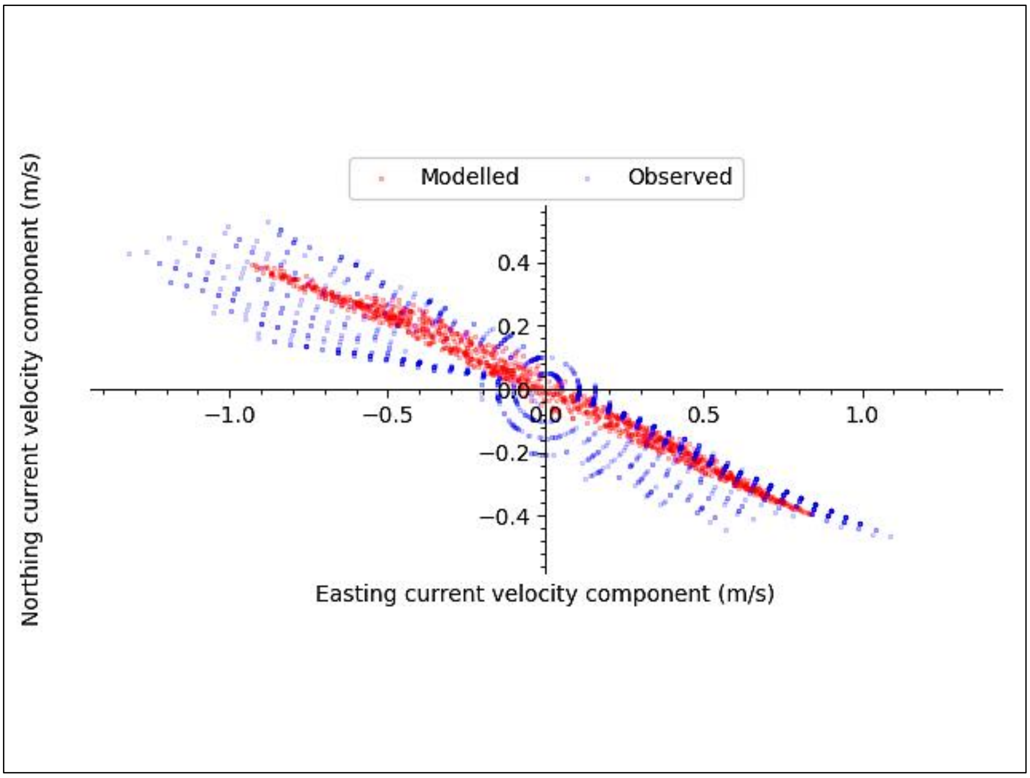

Figure 30 *Scatter plot of observed and modelled velocity from 11th- 29th August 2003 at measurement location SN023F.*

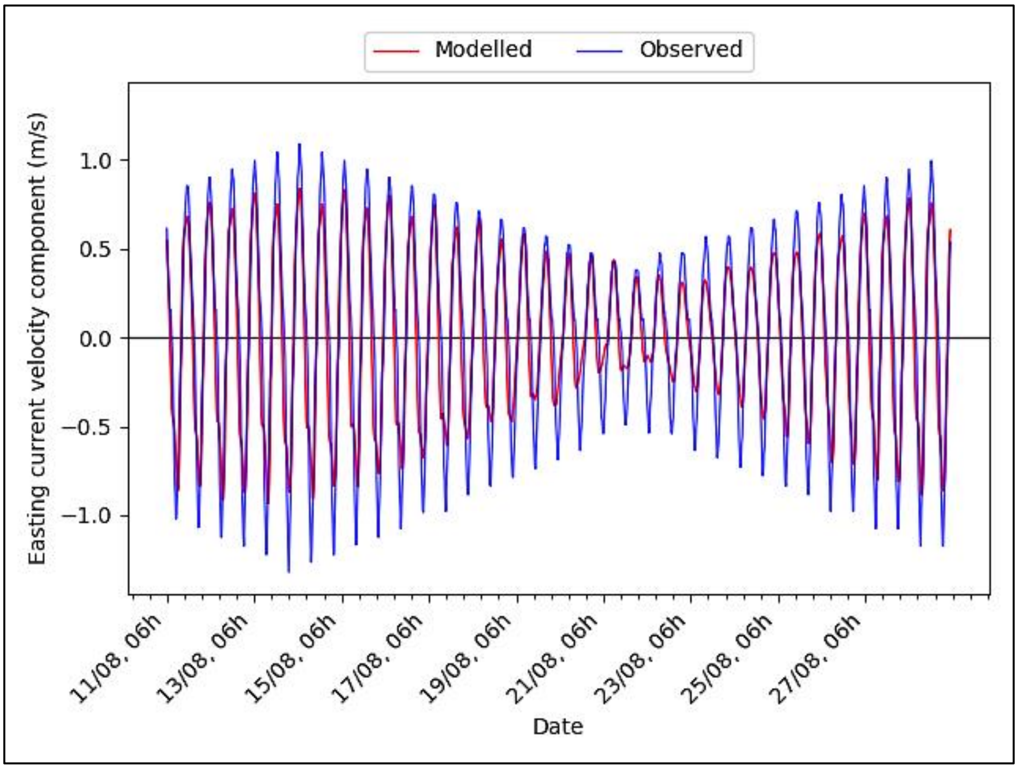

Figure 31 *Comparison between observed and modelled Easting velocity component from 11th- 29th August 2003 at measurement location SN023F. Model skill d2 = 0.95.*

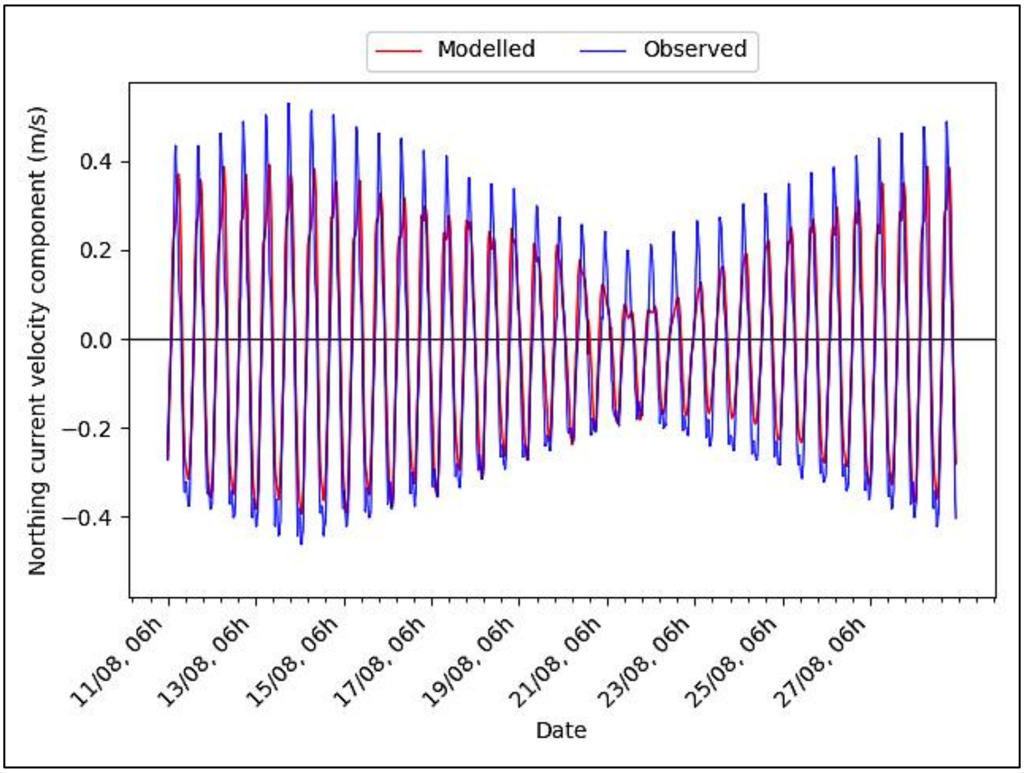

Figure 32 *Comparison between observed and modelled Northing velocity component from 11th- 29th August 2003 at measurement location SN023F. Model skill d2 = 0.96.*

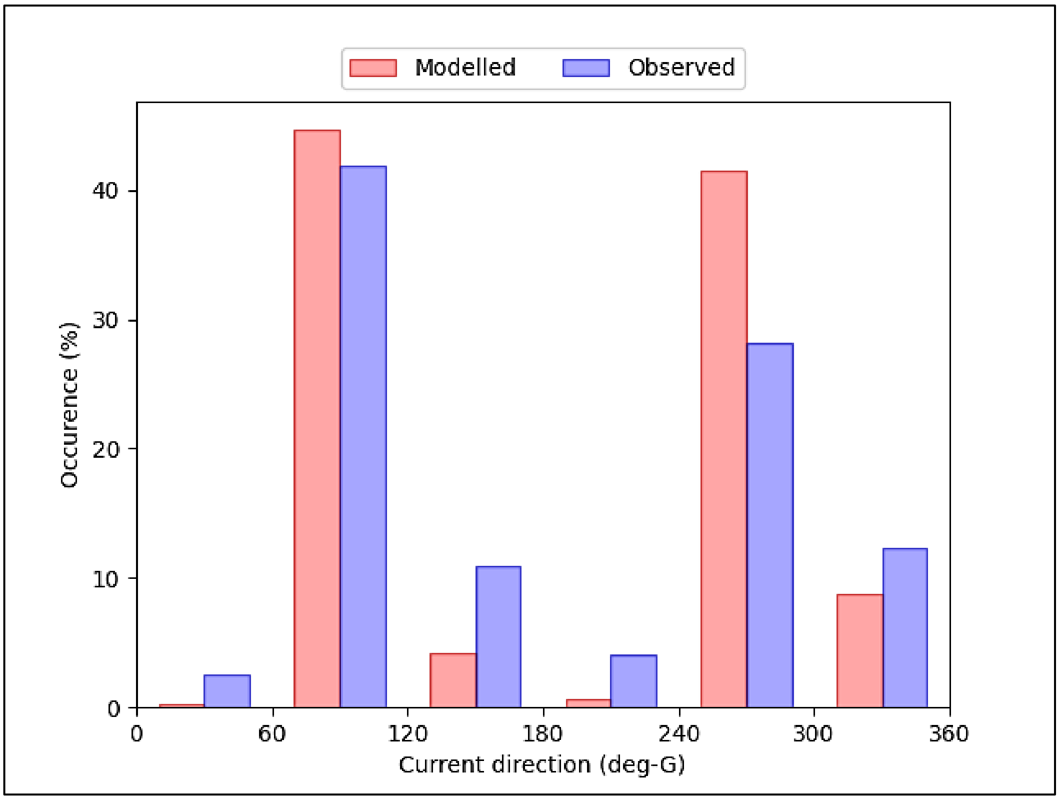

Figure 33 *Histogram of observed and modelled current direction from 11th- 29th August 2003 at measurement location SN023F. Model skill d2 = 0.96.*

3.6 *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 0.148 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 MIKE Queensferry study was 0.21 m compared with the Telemac value of 0.16 m. 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 Firth of Forth and Forth estuary has been constructed using the Telemac code [TELEMAC, 2024]. The 3D model extends from the Kincardine bridge in the West into the North Sea, covering coastal areas to the North coast of Fife and Eyemouth in the East.

The model correctly simulates tide propagation over the Firth of Forths 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 previous work [FRC, 2009].

The Telemac model provides general insight into spatial and temporal variations in the flow environment in the Firth of Forth and Forth estuary. It offers a suitable basis for assessing near-field and far-field dispersion effects of particulate biological matter such as Escherichia coli (E. coli).

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