A Hydrodynamic Model of the West Coast of Scotland – Validation Case Studies

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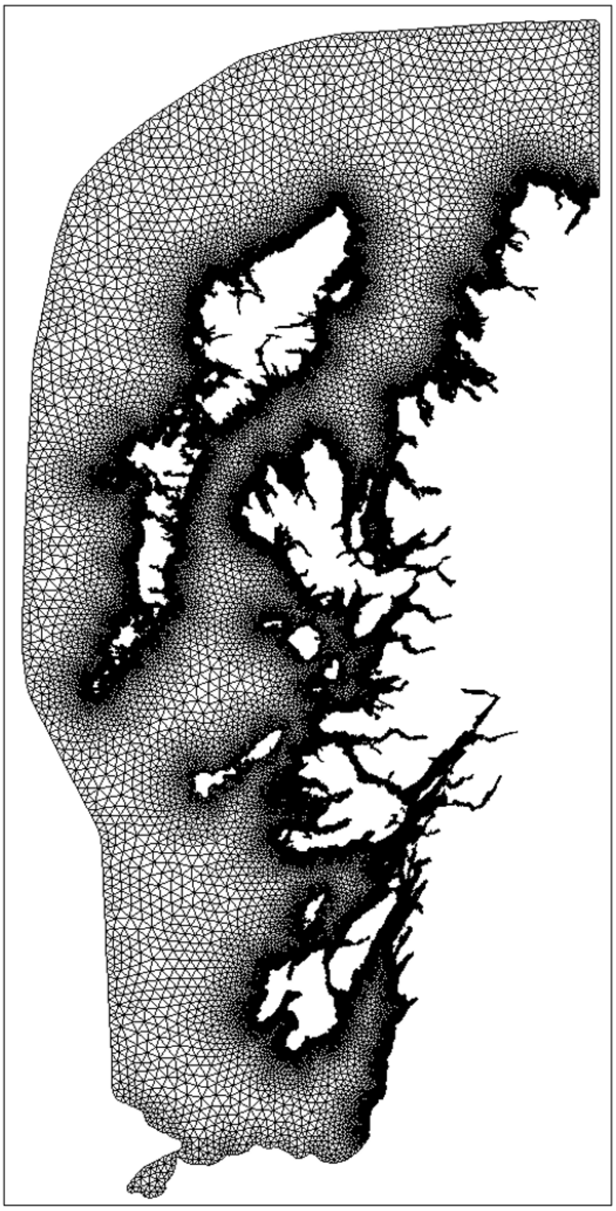

Executive Summary

A three-dimensional hydrodynamic (HD) model of the West Coast of Scotland was constructed using the Telemac3D code (Telemac, 2021). The 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. This report focuses on the validation of the model against physical observations in Loch Hourn and Loch Linnhe.

The oceanography of the West Coast is an area of complex water circulation exhibiting various levels of density stratification throughout the year. The capture of such three-dimensional phenomena necessitates that a 3D, non-hydrostatic approach is used. Freshwater sources from local rivers discharging into the Loch Hourn and Loch Linnhe 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.

The 3D HD model was validated against published observed hydrographic data (water levels and currents) from around the West Coast and in Loch Hourn and Loch Linnhe. This included the long-term tide gauges operated by the British Oceanographic Data Centre (BODC) and short-term current surveys performed by the salmon farm operators and Marine Scotland.

The model correctly simulates the propagation of the tide over the West Coast, with a satisfactory validation against observed water levels at different locations. It was also found that the 3D HD model provides a reasonable description of the flow currents within Loch Hourn and Loch Linnhe, in terms of the current magnitudes, directions, salinity and temperature levels.

It is concluded that the Telemac3D hydrodynamic model can capture the general dynamics of the water levels and current circulation around the West Coast of Scotland with a specific focus on Loch Hourn and Loch Linnhe.

This model offers general insight into the spatial and temporal variation in the flow environment around the West Coast of Scotland. The hydrodynamic model provides 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.

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 hydrodynamic setting

This report has been prepared for the Coastal Communities Network Scotland (CCN), by engineering consultants MTS-CFD and Plastic@Bay, as part of hydrodynamic modelling services to consider the impact of sea lice 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, pesticides and live parasitic salmon lice.

The report describes the development of a hydrodynamic model of the West Coast of Scotland, simulating water levels and flows (i.e., currents and tides), with a focus on Loch Hourn and Loch Linnhe for code validation. Figure 1 shows the extent of the computational model and the locations of Loch Hourn and Loch Linnhe.

The coastline of north-west Scotland is notable for its complex topography. Glaciation has formed a great number of islands and peninsulas, while many sounds and inlets penetrate deep into the land. Numerous glacially deepened basins exist, offshore and in the sounds and inlets. The basins and narrow canyons of the sea and loch bed bathymetry are often separated by relatively shallow sills possibly of morainic or resistant rock origin (Edwards, 1986).

Water in the regional seas around Scotland's West coast is derived from three sources: oceanic or Atlantic water, Clyde/Irish Sea water and coastal water discharging from the land (Offshore Energy SEA, 2021). Overall circulation patterns (Figure 2) inferred from the distributions of salinity and temperature, and direct water circulation measurements, indicate a net northward transport along the Scottish west coast, both through the Sea of the Hebrides and the Minch and to the west of the Outer Hebrides (the Scottish Coastal Current). On the basis of observation and drifter experiments (Hill, 1997) described a bifurcation of the northward coastal current in the Sea of the Hebrides, with a proportion of the water mass

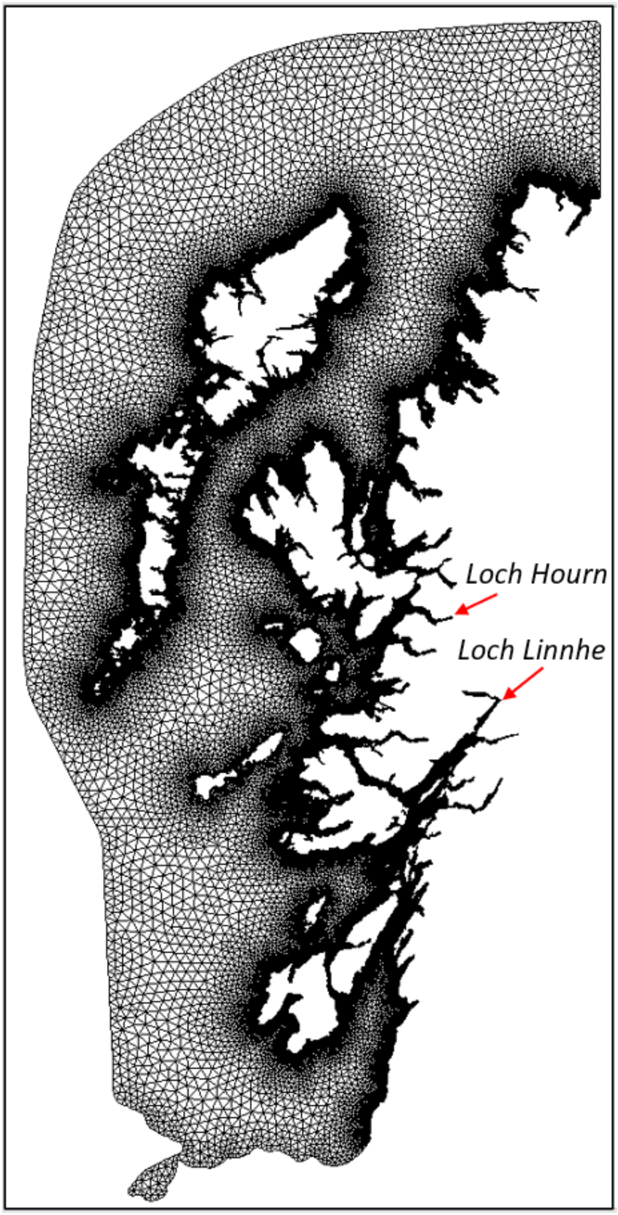


Figure 1 *Extent of computational model and locations of Loch Hourn and Loch Linnhe.*

passing through the Little Minch, and the remainder re-circulating southward towards Barra Head.

This large-scale, organised flow behaviour was also observed (Simpson, 1986) where a notable feature of the current was its interaction with the island chain of the Hebrides. Tracer distributions suggested that on entering the Minch (the channel between Scotland and the islands), part of the flow turned westward, crossed the Minch and flowed southward along the Hebrides coast. This bifurcation of the current was confirmed by current meter observations. Figure 3 shows a snapshot from the Telemac 3D hydrodynamic model presented in this report. Results show the current speed vectors and highlight the southward flow towards Barra Head and the clockwise circulation around the islands of South Uist, Barra and Mingulay as described by (Hill, 1997) and (Simpson, 1986). Further validation of the hydrodynamic model is provided in Section 3 of this report.

Flows within the coastal waters generally represent a zone where freshwater runoff and solar heating act to stratify the water by forming less saline or warmer buoyant layers near the surface, and where winter cooling, wind and tidal mixing tend to homogenise it (Edwards, 1986).

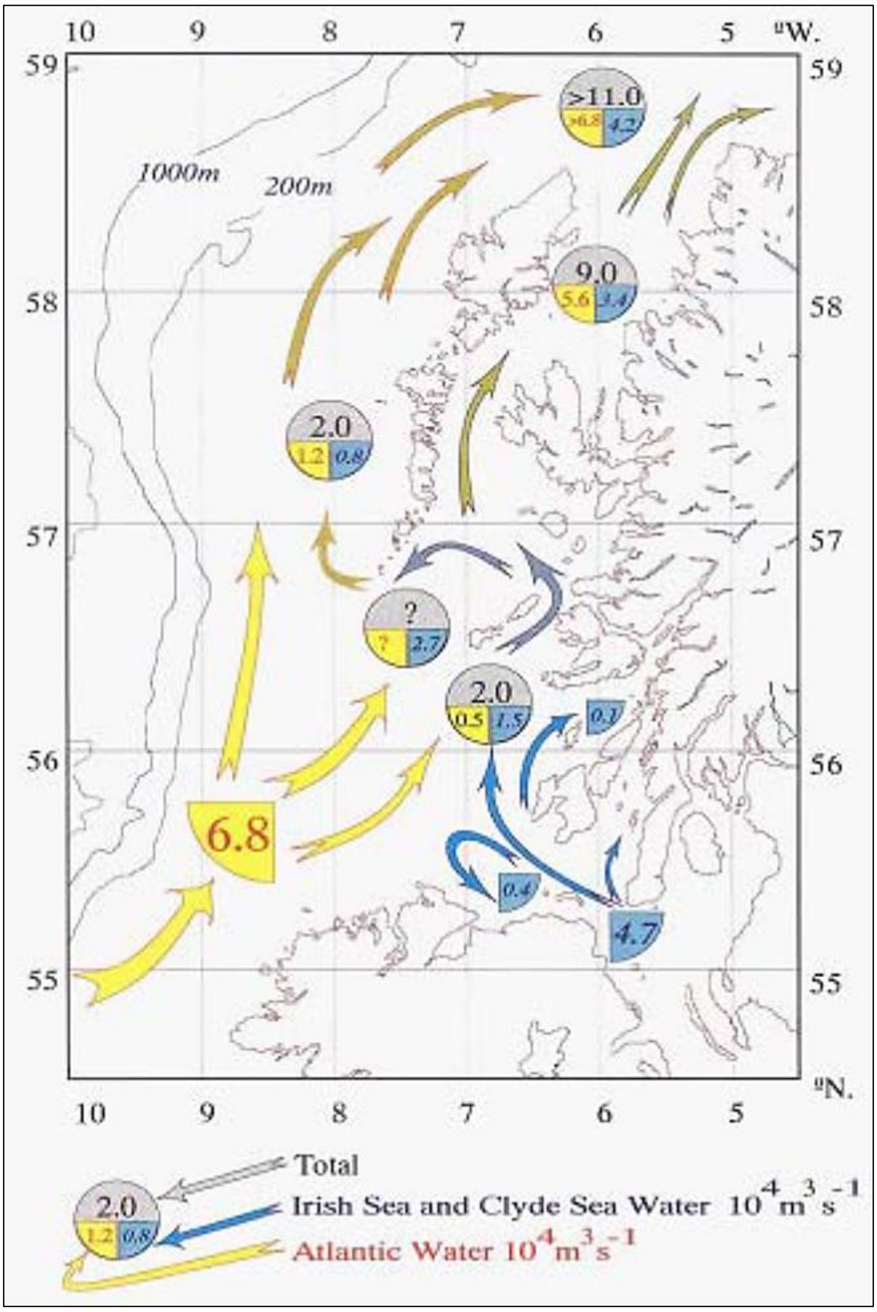


Figure 2 *West Coast of Scotland general circulation patterns and approximate volume fluxes* (*Offshore Energy SEA, 2021*).

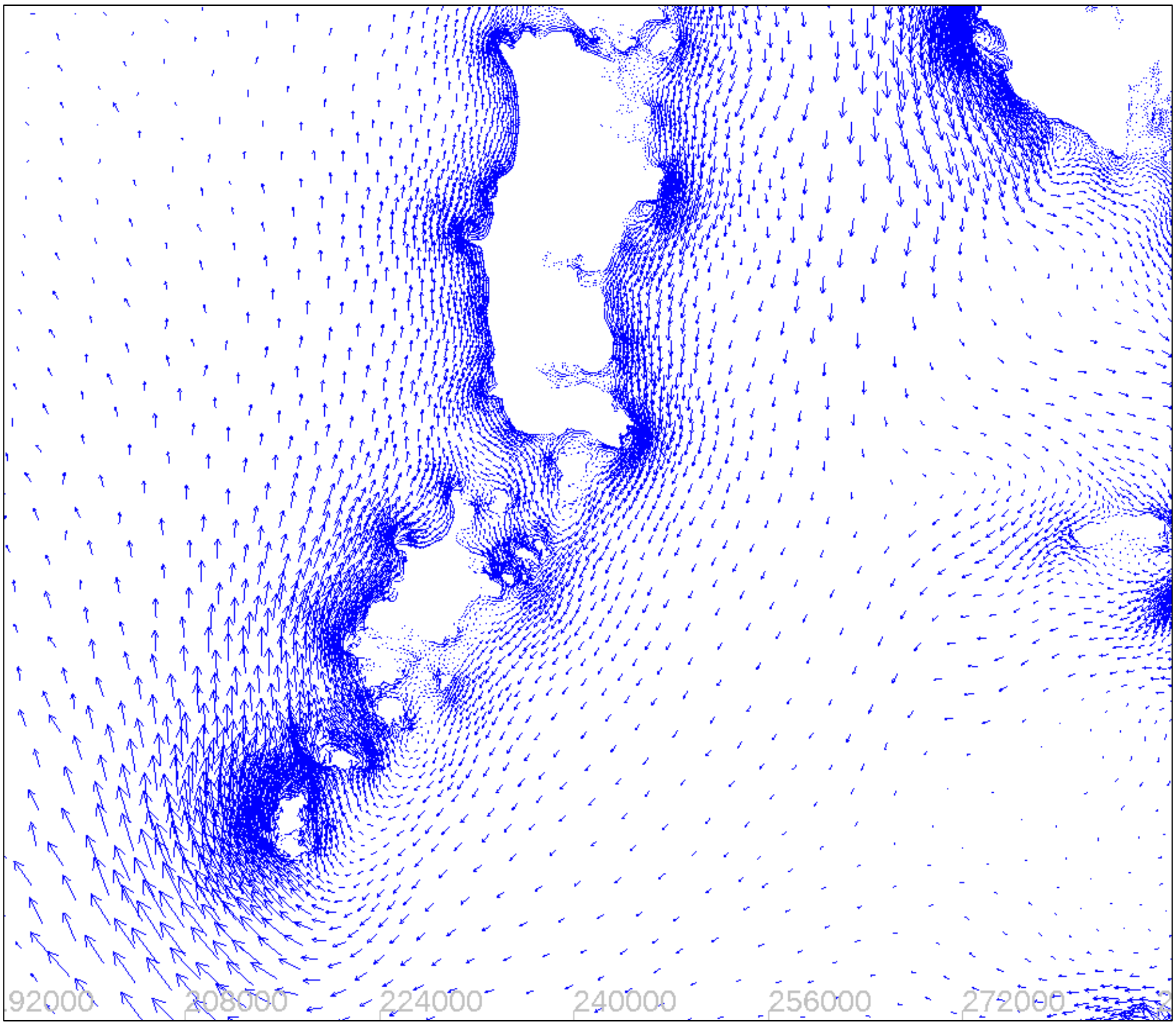


Figure 3 *Example of clockwise circulation around South Uist, Barra and Mingulay produced using the Telemac 3D hydrodynamic model.*

2 Available Data

This section summarises the data used during the modelling process.

2.1 *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, 2021), digitised Admiralty charts and bathymetry information from the UK's Digimap Ordnance Survey Collection (DOSC, 2021). The bathymetry used in the model is shown in Figure 4, while Figures 5 and 6 show the bathymetry in the vicinity of Loch Hourn. Figures 6-8 show the bathymetry in the region of Loch Linnhe. A good comparison is found between the Telemac 3D bathymetry and the Marine Scotland Wider Loch Linnhe System (WLLS) model (SSM_3, 2022).

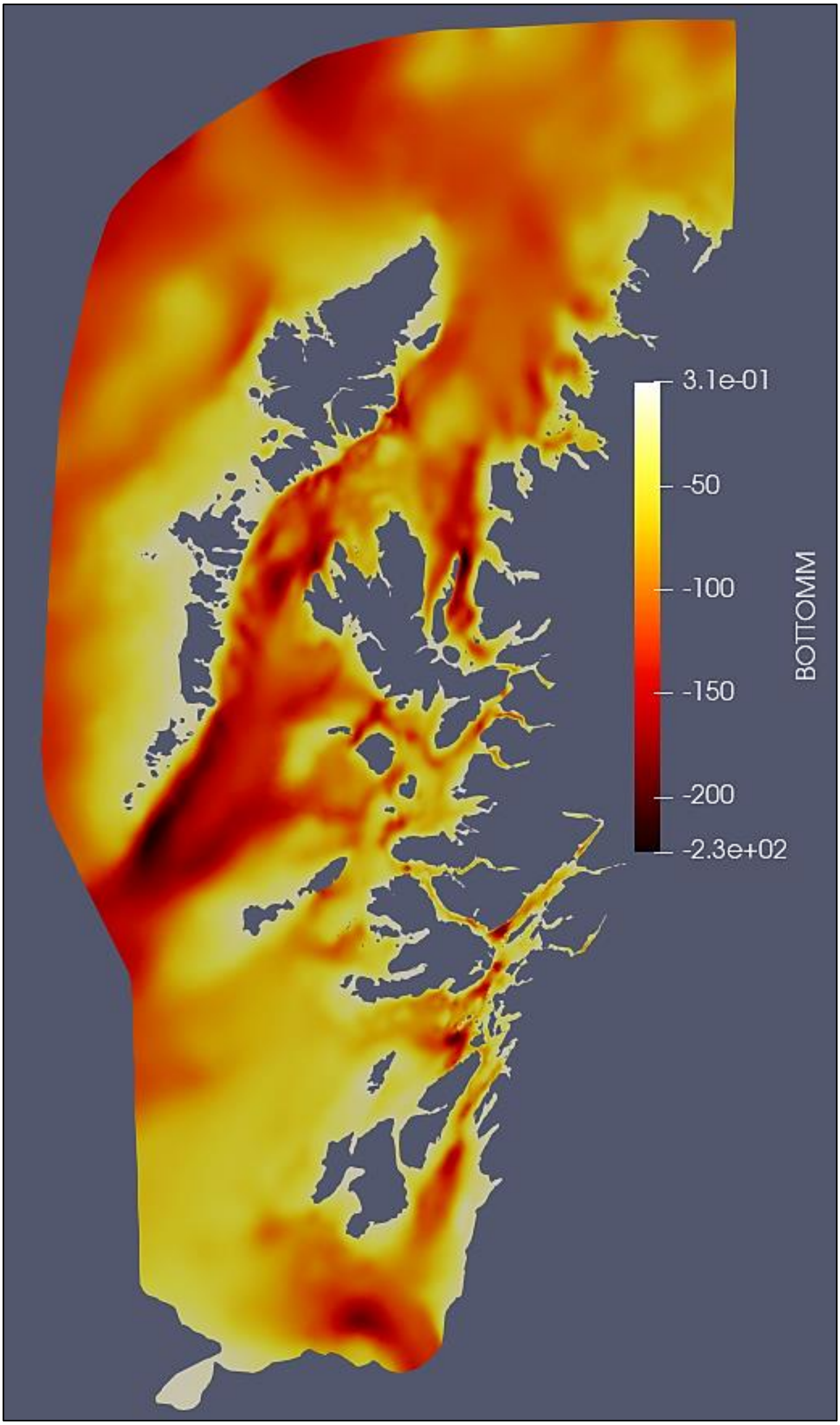


Figure 4 *Model bathymetry (m) and spatial extent of model*

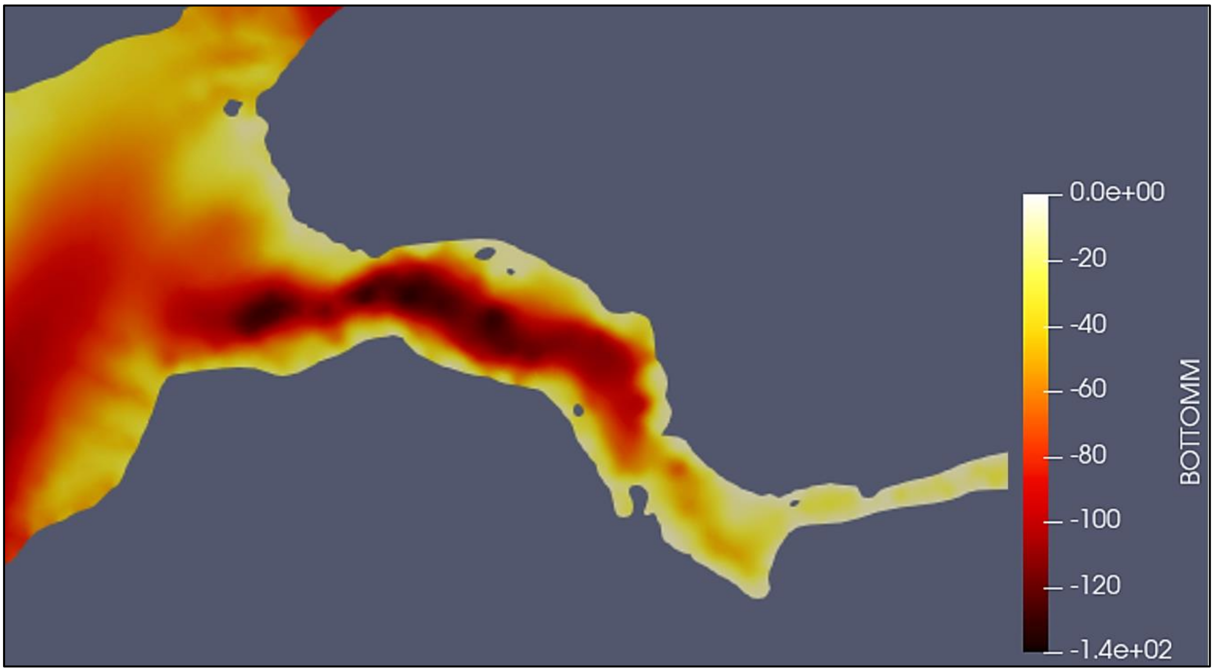


Figure 5 *Model bathymetry (m) in Loch Hourn*

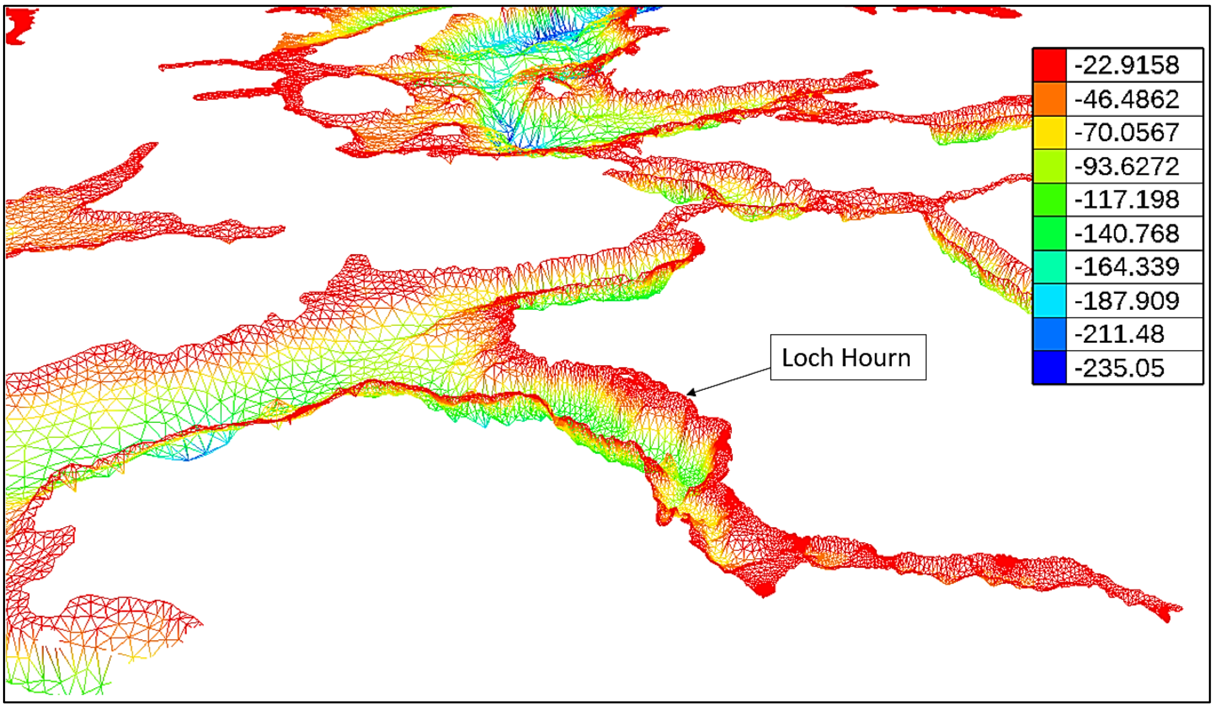


Figure 6 *Model bathymetry (m) in 3D around Loch Hourn*

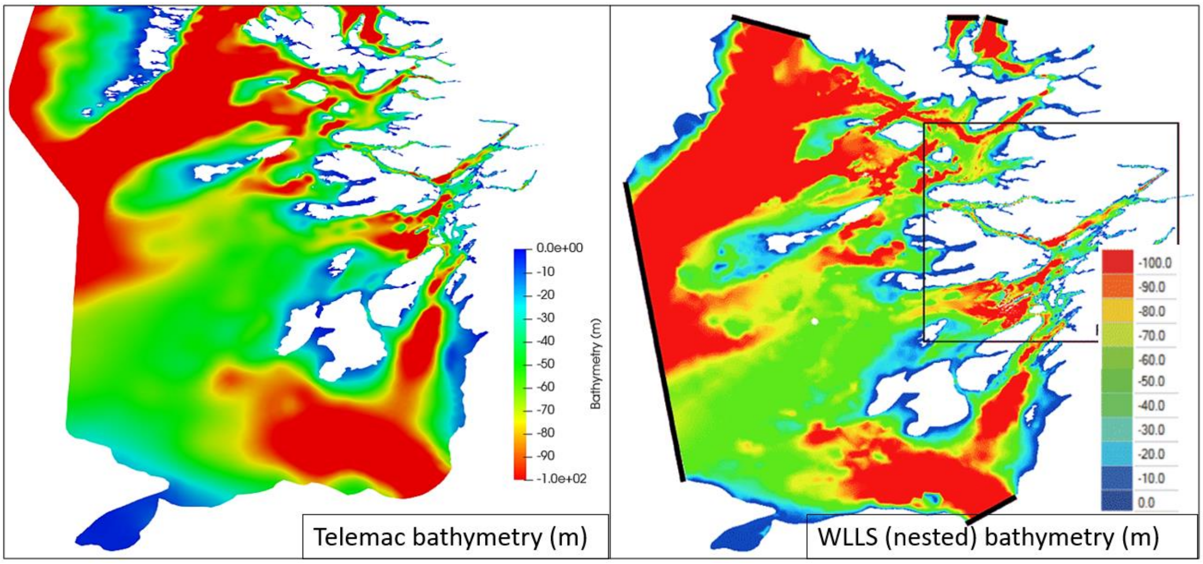


Figure 7 *Model bathymetry (m) near Loch Linnhe. Telemac (left), Marine Scotland Wider Loch Linnhe System (WLLS) model (right).*

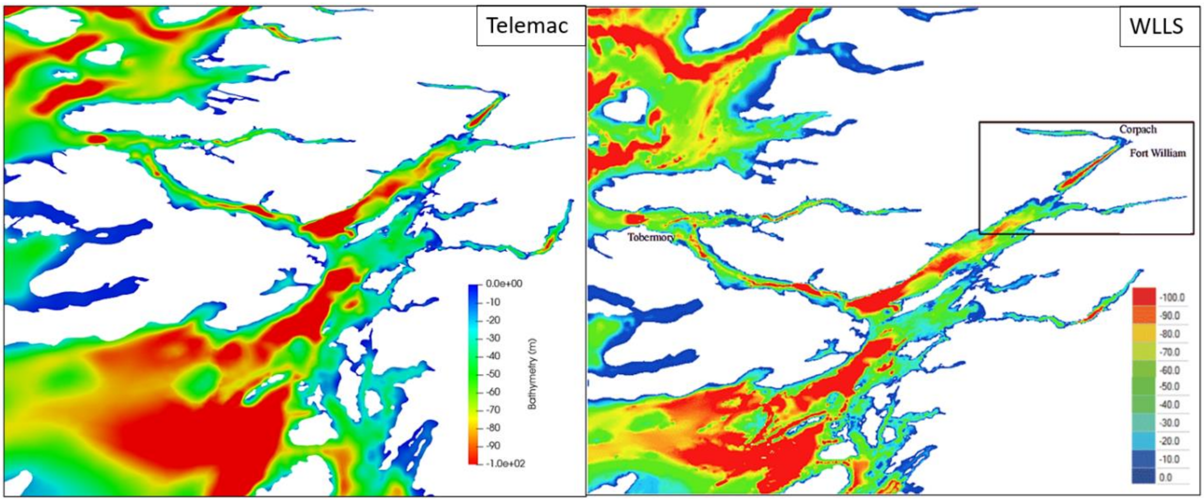


Figure 8 *Model bathymetry (m) near Loch Linnhe zoomed. Telemac (left), Marine Scotland Wider Loch Linnhe System (WLLS) model (right).*

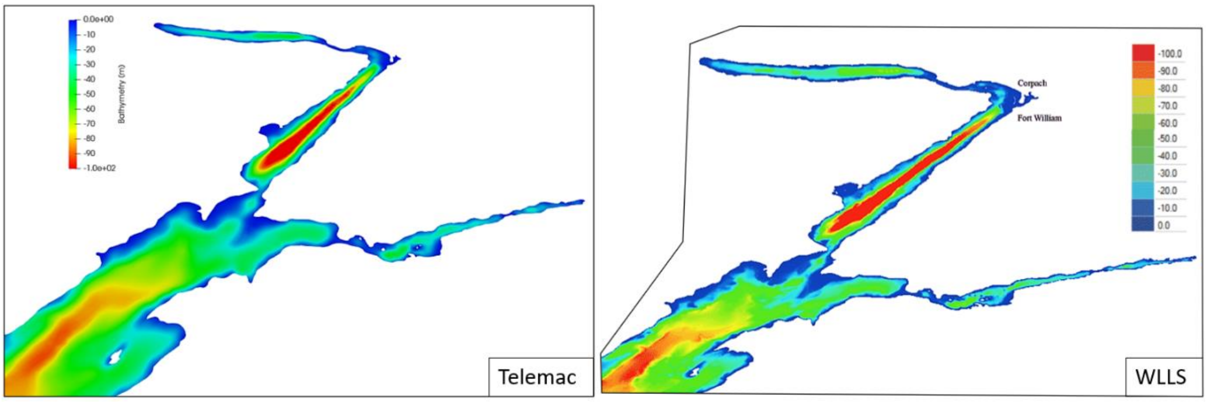


Figure 9 *Model bathymetry (m) in upper Loch Linnhe. Telemac (left), Marine Scotland Wider Loch Linnhe System (WLLS) model (right).*

2.2 *Water levels*

Information on water levels was obtained from the UK Tide Gauge Network, which is owned and operated by the Environment Agency on behalf the UK Coastal Flood Forecasting service (UKCFF).

Data from the UK Tide Gauge Network is made available through the British Oceanographic Data Centre (BODC, 2021) who have responsibility for the monitoring and retrieval of sea level data. Daily checks are kept on the performance of the gauges and the data are downloaded weekly.

The data were extracted from stations 1,3,4 and 5 shown in Figure 10 for the period 1st – 31st October 2010. Sea level data were also provided by Mowi at the Loch Hourn salmon farm (location 2) for the period 28th November 2018 to the 11th January 2019. The water level data were provided relative to Chart Datum (CD). Data processing consisted of converting levels relative to mean-sea-level by de-trending the data (i.e., by subtracting the signal mean).

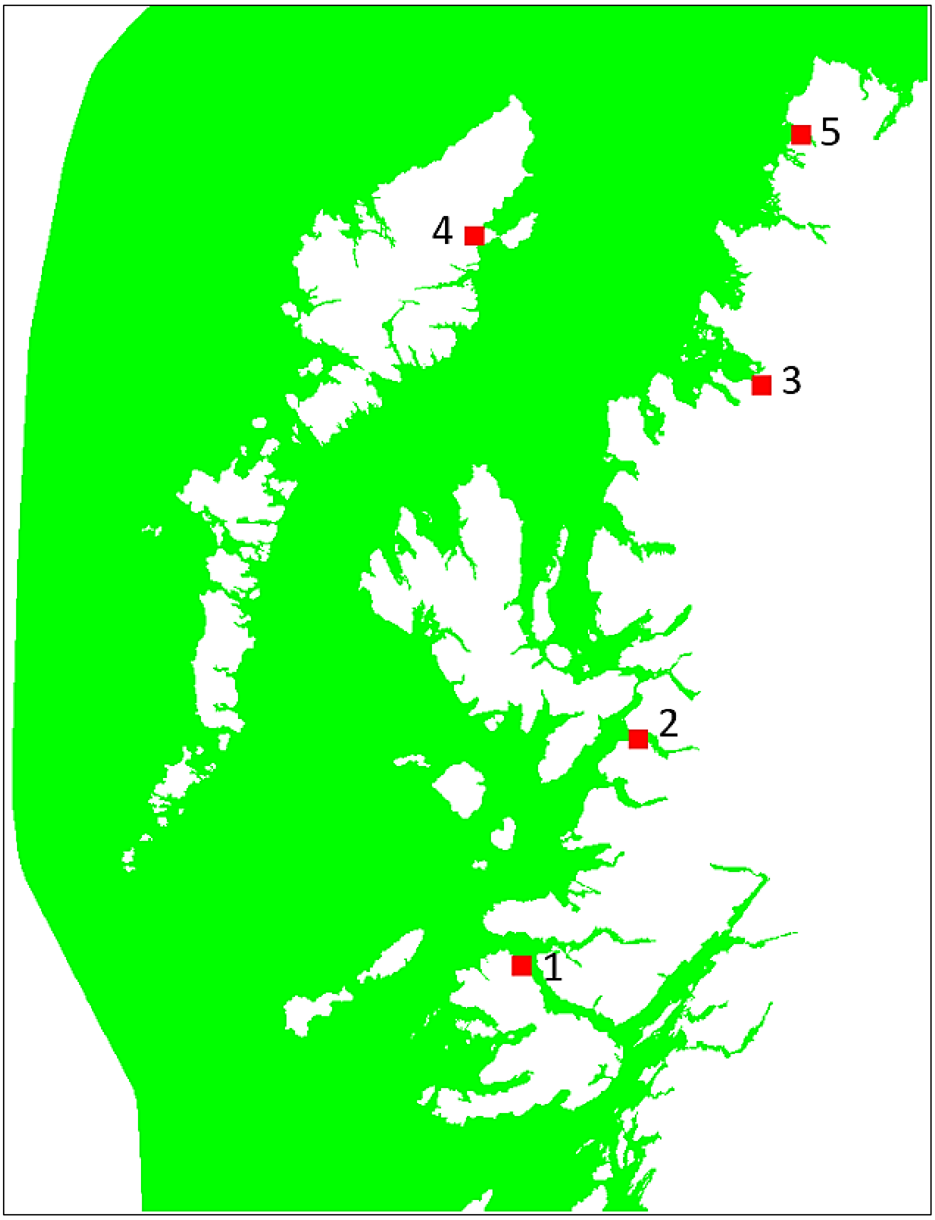


Figure 10 *Map showing location of sea level observation stations:*

1 Tobermory, 2 Loch Hourn, 3 Ullapool, 4 Stornoway, 5 Kinlochbervie

For Loch Linnhe, water level data were provided by Marine Scotland at Fort William and Southern Loch Linnhe at the locations shown in Figure 11. The time period for the Marine Scotland data was 1st-31st May 2011.

Figure 11 *Map showing Marine Scotland water level gauge locations at Fort William (left) and Southern Loch Linnhe (right).*

2.3 *Currents*

2.3.1 *ADCP Current Meters*

Information on current speeds in Loch Hourn were obtained from data produced by the salmon farm company Mowi at the Loch Hourn salmon farm. These data were recorded during a series of Acoustic Doppler Current Profiler (ADCP) measurements. Figure 12 shows the location of salmon farm at Loch Hourn.

The ADCP meters are mounted on the seabed and use an acoustic signal to record the current velocities at various depths (bins) through the water column. The near-surface current speed (m/s) was used for model validation purposes.

For Loch Linnhe, the ADCP current data was extracted in mid-Loch Linnhe at the location shown in Figure 13.

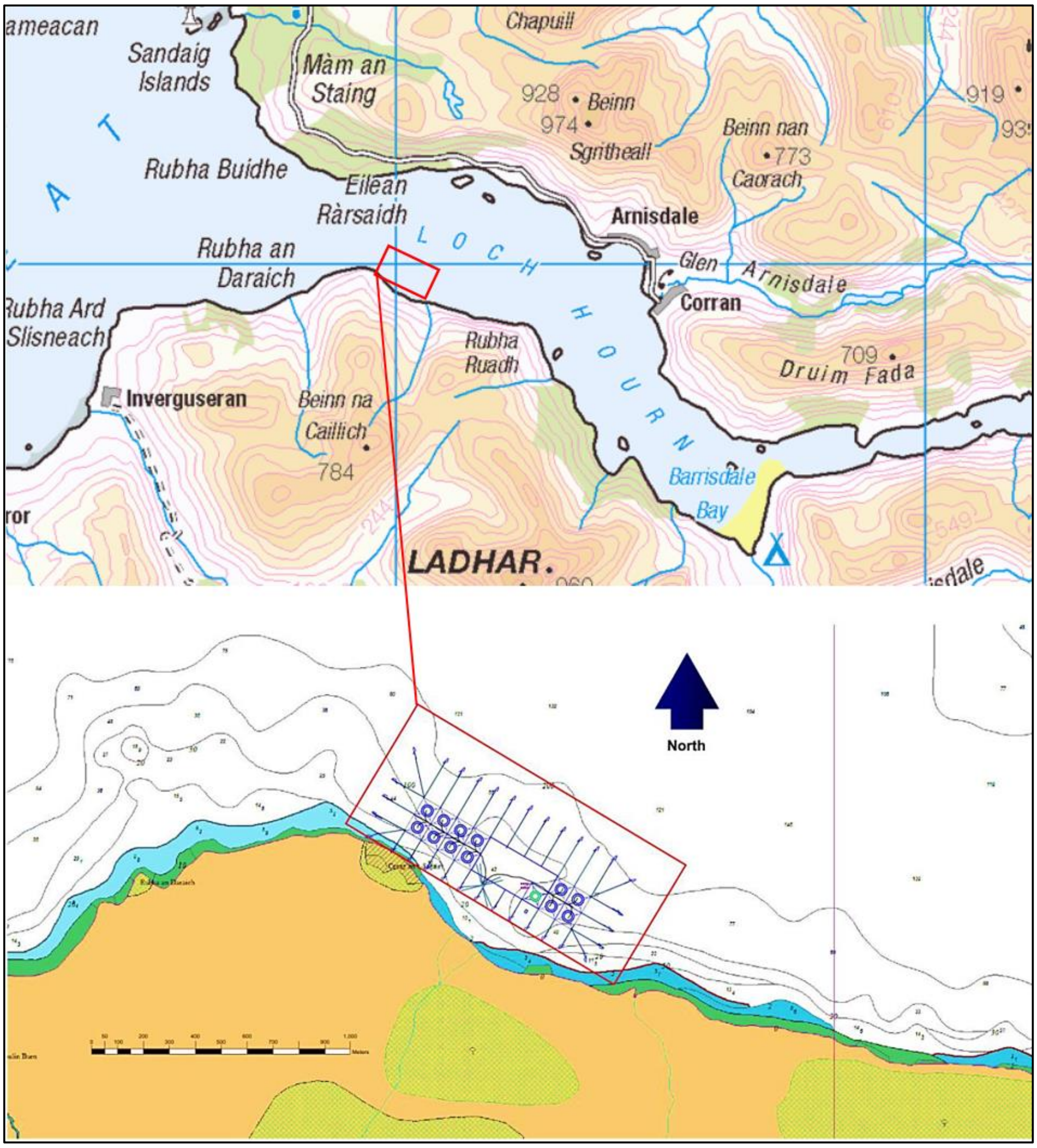


Figure 12 *Map showing location of the salmon farm at Loch Hourn.*

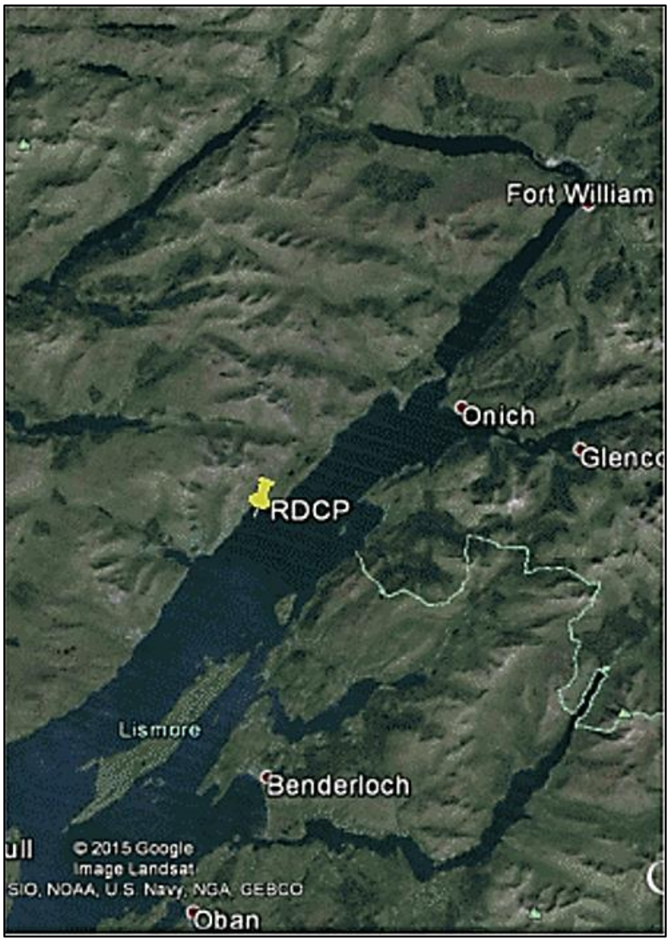


Figure 13 *Map showing location of current measurement at mid-Loch Linnhe.*

2.4 *Meteorological data*

Meteorological data consist of information on wind air speed, direction and temperature. Wind data were extracted from an on-line resource (Time and Date, 2021). The historic data for wind speed, direction and temperature are available on a six-hourly average basis and the data correlated with the time duration of the model run.

2.5 *Freshwater sources*

Data for freshwater sources (i.e., river run off) entering Loch Hourn, Loch Linnhe and the surrounding areas were identified from the historical flow estimates from the network of hydrometric stations operated by SEPA and made available via the National River Flow Archive (NRFA). These data consisted of estimates of daily mean river flow for gauged catchments from 1960 to 2015 (G2G, 2018).

Figure 14 shows the location of the 40 freshwater discharge locations included in the Loch Hourn model run.

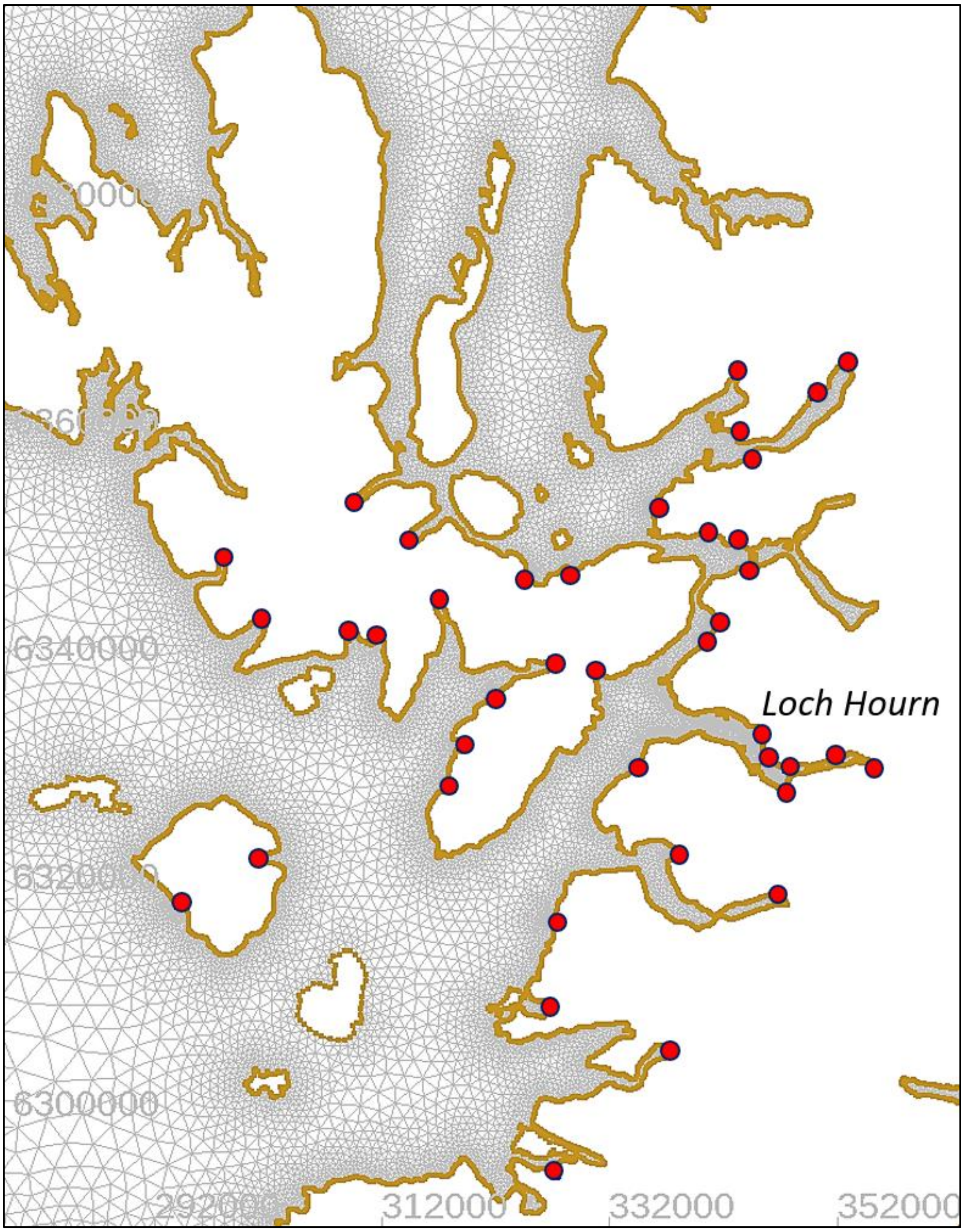


Figure 14 *Map showing location of 40 freshwater discharges for the Loch Hourn model run.*

A further 45 rivers were added from the G2G, 2018 dataset for the Loch Linnhe model run. This produced a total of 85 flow inlets that are shown in Figure 15.

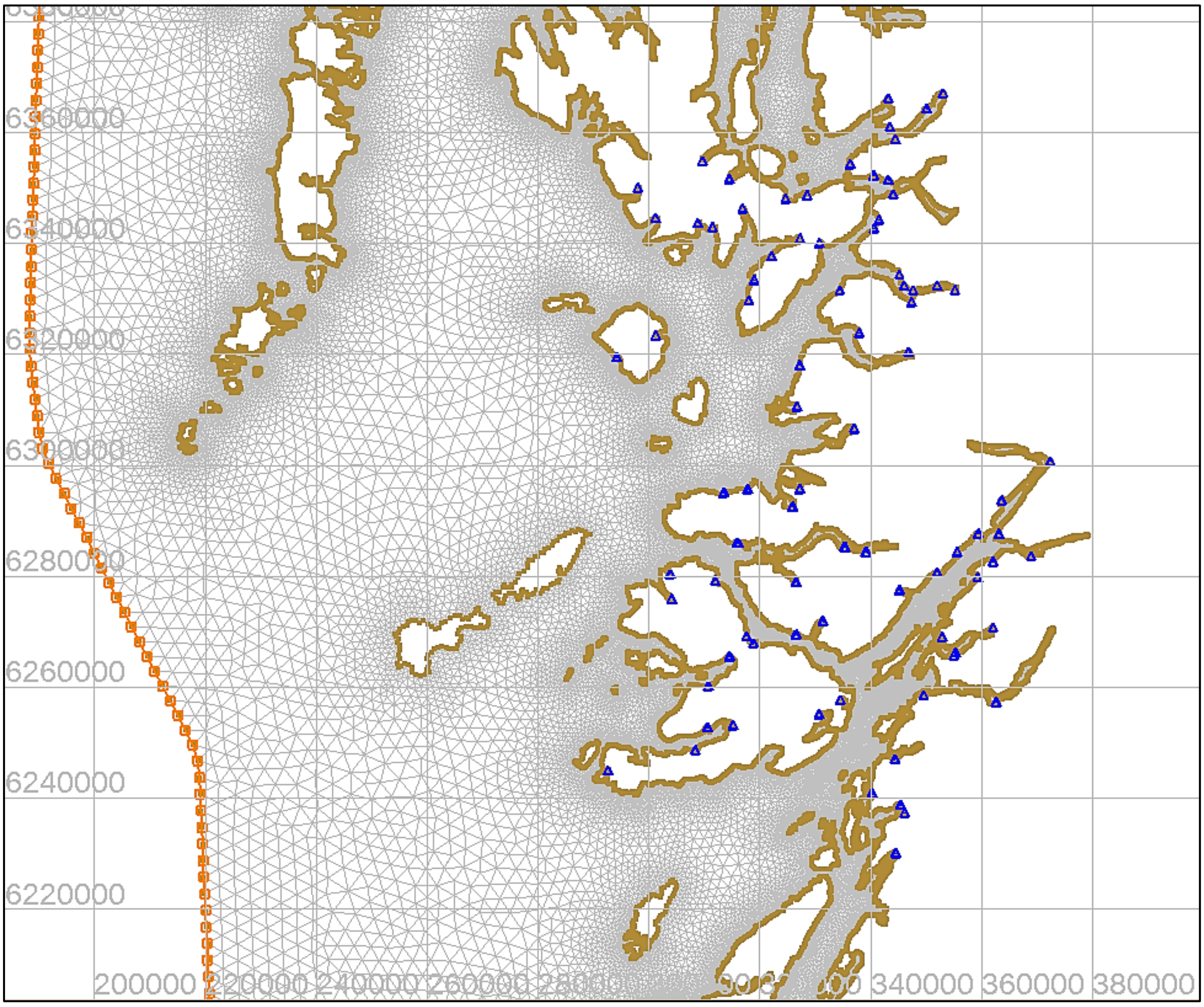


Figure 15 *Map showing location of 85 freshwater discharges (blue triangles) for the Loch Linnhe model run.*

2.6 *Salinity and temperature*

Information on the salinity and temperature fields in Loch Hourn were provided by (Mowi, 2021) as shown in Figure 16. This data was used as a resource to allow validation of the Telemac hydrodynamic model results.

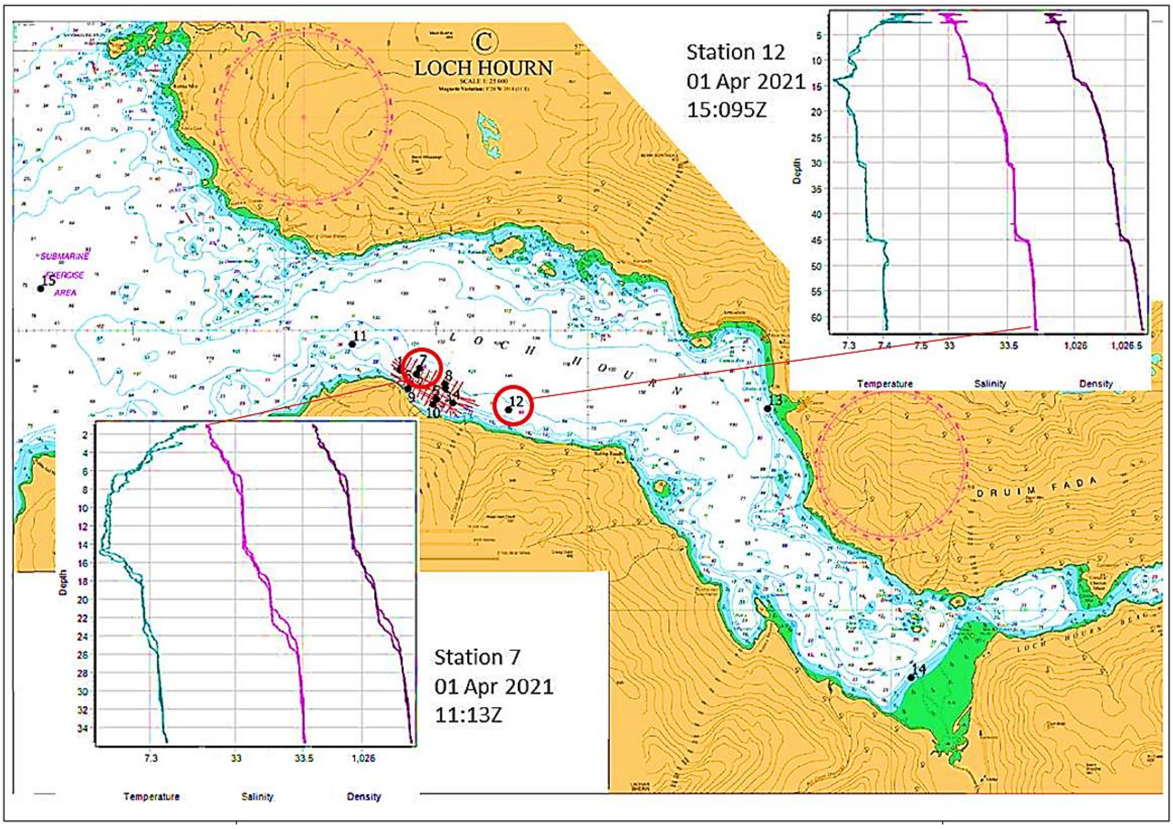


Figure 16 *Map showing location of salinity and temperature measurements in Loch Hourn by Mowi.*

For Loch Linnhe, Marine Scotland have gathered data on salinity and temperature at the upper-Loch Linnhe data buoy location shown in Figure 17 and at the mid-Loch Linnhe locations shown in Figures 18 and 19.

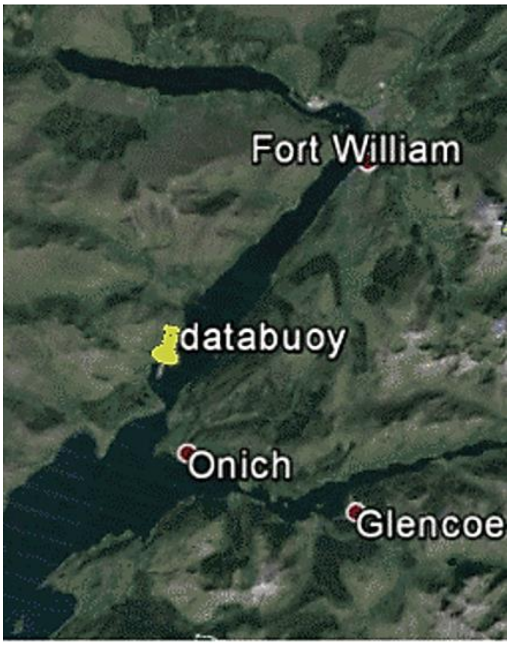


Figure 17 *Data buoy location for salinity and temperature in upper-Loch Linnhe.*

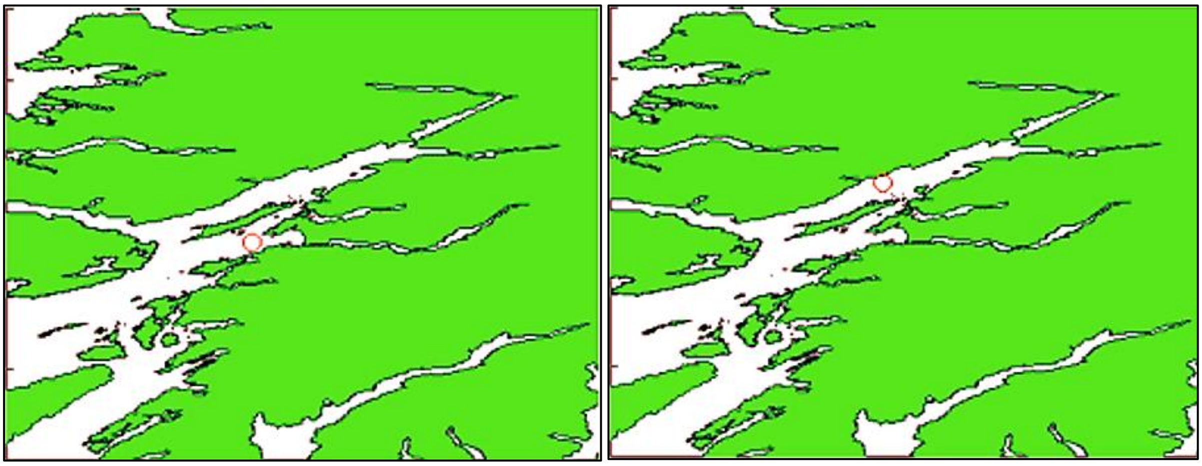


Figure 18 *Salinity and temperature measurement location 1 (left) and 2 (right) in mid-Loch Linnhe (red circles).*

3 Model Development

3.1 *Model selection*

The Telemac3D Flow code (Telemac, 2021) is an open-source modelling system for 3D free-surface flows. Having been used in the context of many flow studies throughout the world, it has become one of the major standards in its field.

The Telemac code is managed by a consortium of core organisations: *Artelia* (formerly Sogreah, France), *Bundesanstalt für Wasserbau* (BAW, Germany), *Centre d'Etudes et d'Expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement* (CEREMA, France), *Daresbury Laboratory* (United Kingdom), *Electricité de France R&D* (EDF, France), and *HR Wallingford* (United Kingdom).

The software is listed as an "*example of numerical hydrodynamic technologies*" by SEPA (SEPA, 2021) and is also listed as a hydrodynamic technology by the Crown Estate (UK Crown Estate, 2021).

The model system is based on the numerical solution of the 3D incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of the Boussinesq approximation and a non-hydrostatic pressure option. The model is applicable for the simulation of hydraulic and environmental phenomena in lakes, estuaries, bays, coastal area, and seas. The model can be used to simulate a wide range of hydrodynamic and related items, including tidal exchange, currents, and storm surges.

The HD module is the cornerstone of the Telemac Flow Model. The HD module simulates water level variations and flows in response to a variety of forcing functions. The 3D model described in this report includes:

- Bottom shear stress;
- Wind shear stress;
- Effects of stratification

- Freshwater sources;
- Flooding and drying;
- Tidal potential;
- Coriolis force;

The Telemac model in this document is based on unstructured triangular elements and applies the finite element numerical solution technique.

3.2 *Domain, mesh and ocean physics*

3.2.1 *Model domain*

The domain of the Telemac model developed for West Coast study is shown in Figure 19. The horizontal reference was chosen as UTM Zone 30 N. The model domain extends from the Mull of Kintyre in the south to Cape Wrath in the north and includes all of the main islands and sea lochs of Scotland's West Coast.

Two open (sea) boundaries are located in the North Channel and Atlantic Ocean. The northern boundary extends from the north coast of Scotland near Loch Eriboll around the Outer Hebrides to Malin Head (Republic of Ireland). The southern boundary spans the North Channel from a location near Torr Head (Northern Ireland) to the Mull of Kintyre (Scotland).

3.2.2 *Computational mesh*

The computational mesh was constructed using a flexible mesh approach with a varying spatial resolution (i.e., element length) across the domain (Figure 4.1). Mesh resolution was down to 3 km at open sea boundaries and a few tens of metres at river inlets. The Telemac mesh was generated using the freely-available *BlueKenue* code (Blue Kenue 2021) and there were a total of 1,341,730 nodes and 6,494,310 elements in mesh. Ten vertical terrain-following sigma layers were employed to account for the sea depth.

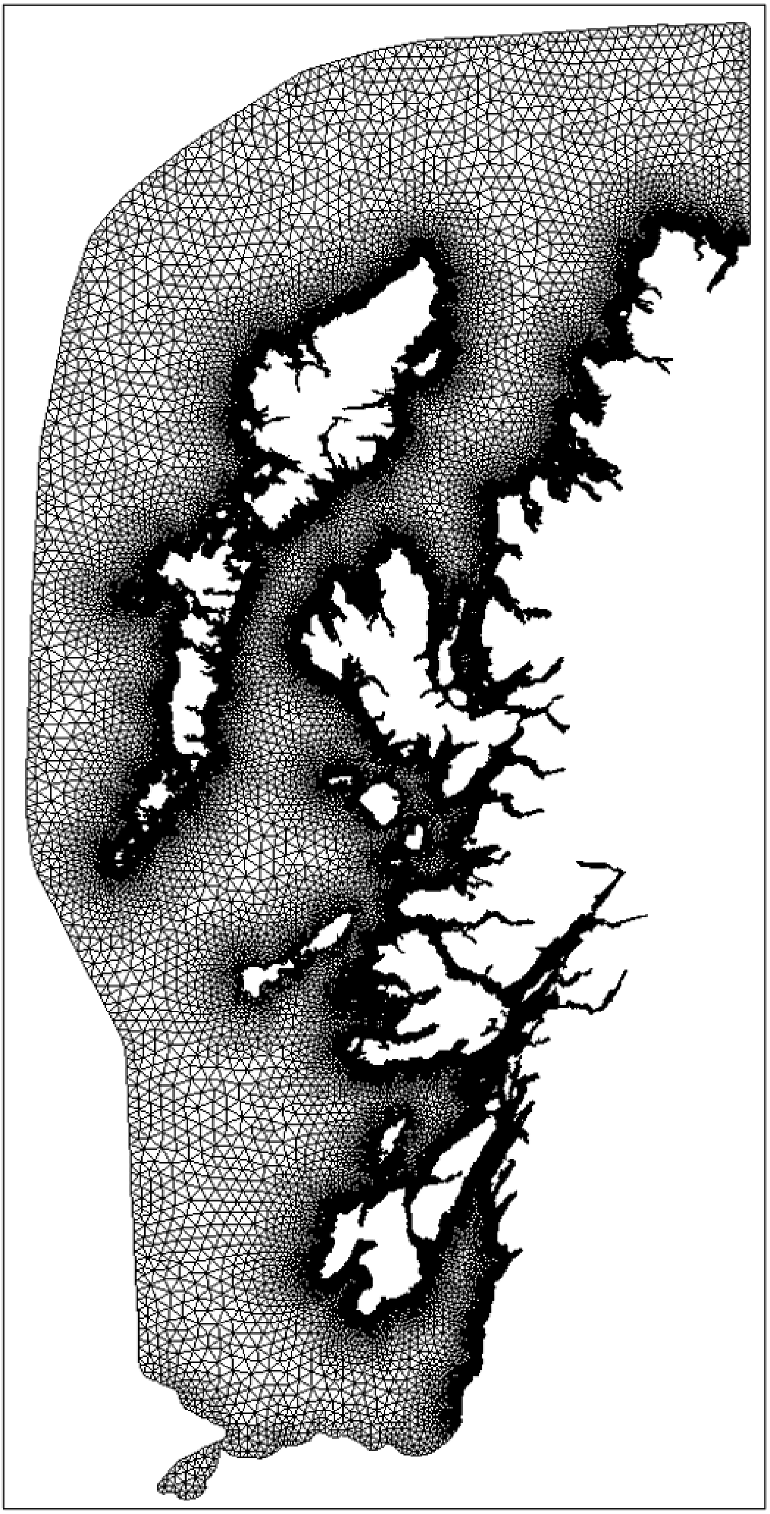


Figure 19 *Telemac mesh over the entire computational domain.*

Figures 20 to 22 show the computational mesh in the upper, middle and lower regions and Figure 23 shows the higher resolution mesh developed for Loch Hourn itself.

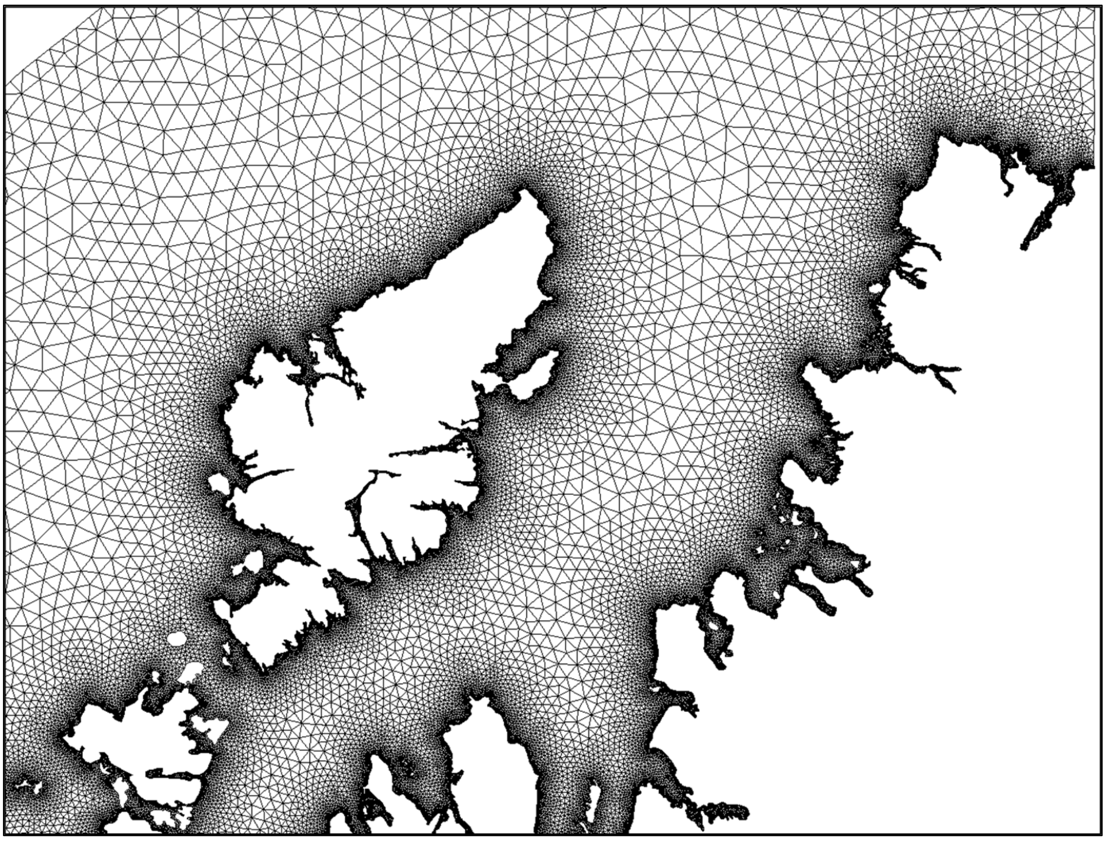


Figure 20 *Telemac mesh over the Northern section.*

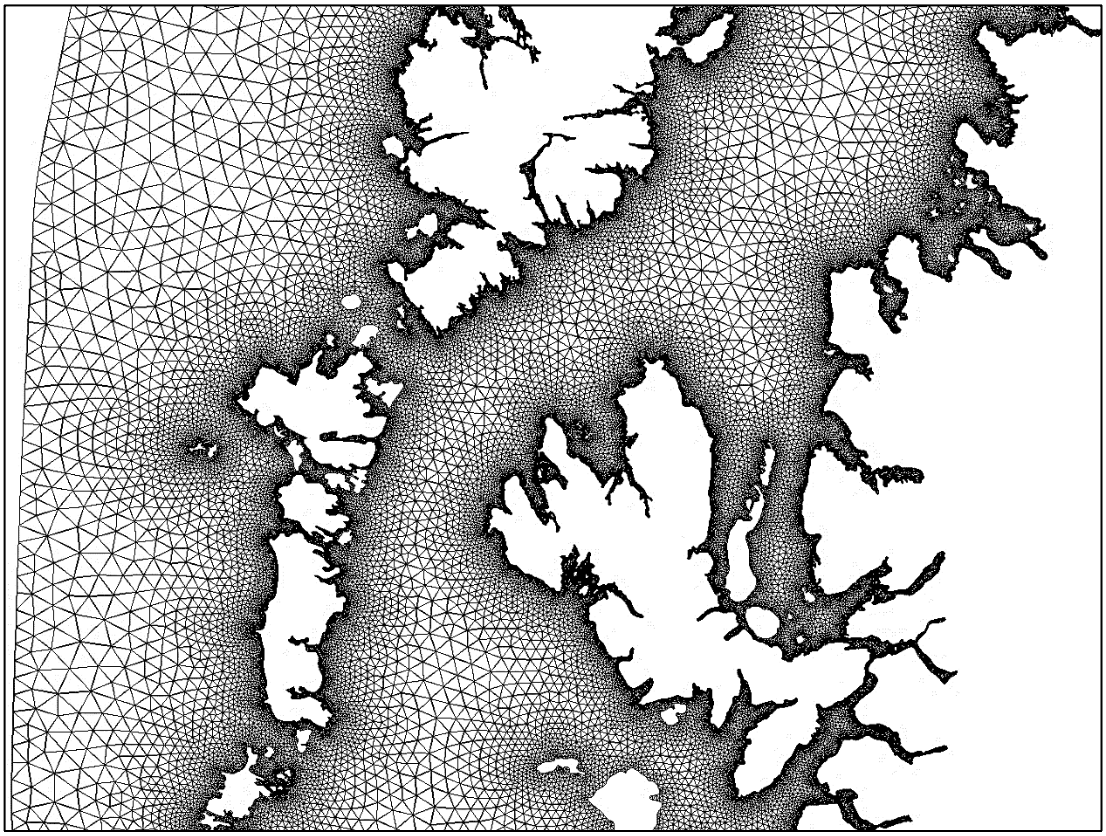


Figure 21 *Telemac mesh over the middle section.*

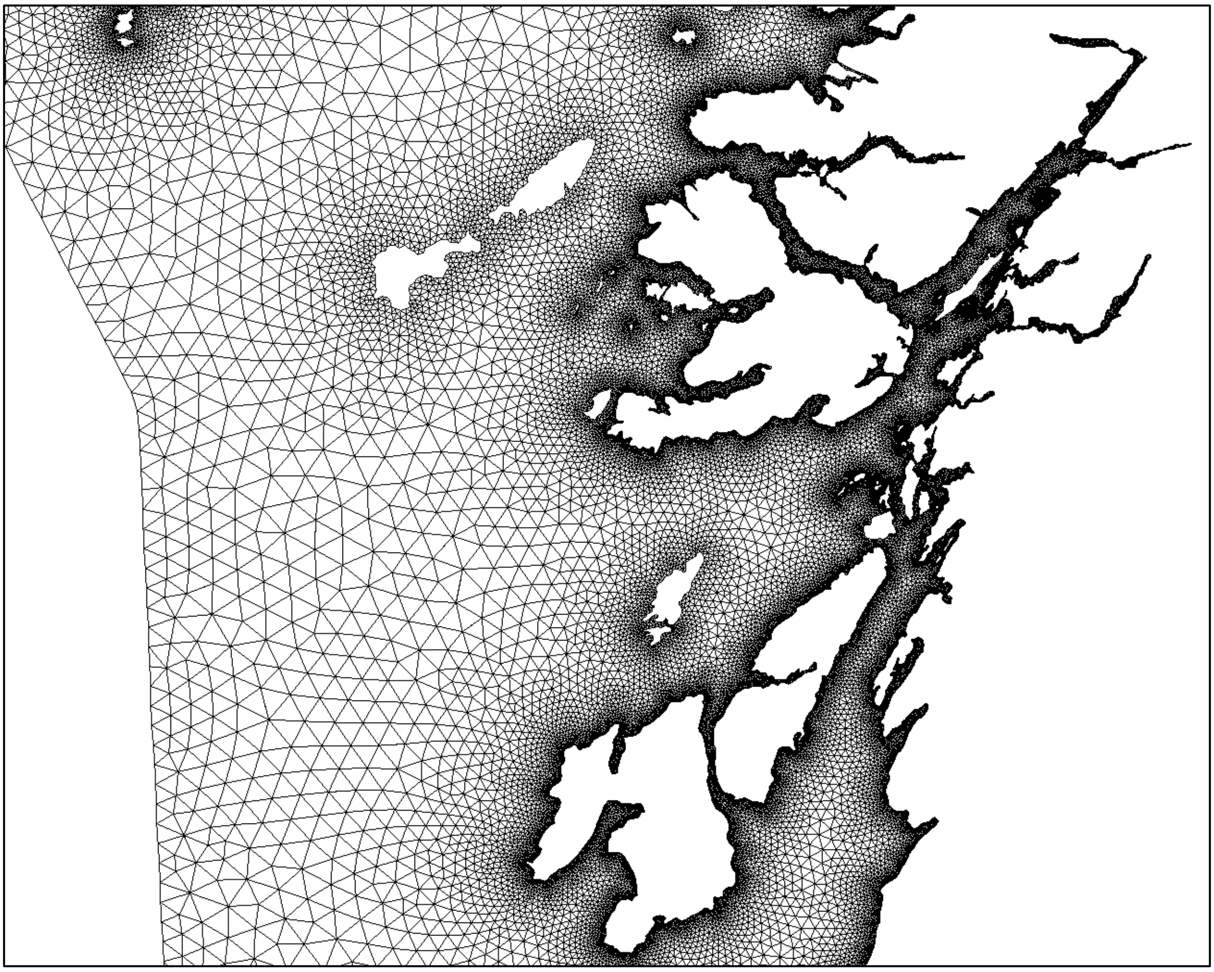


Figure 22 *Telemac mesh over the Southern section.*

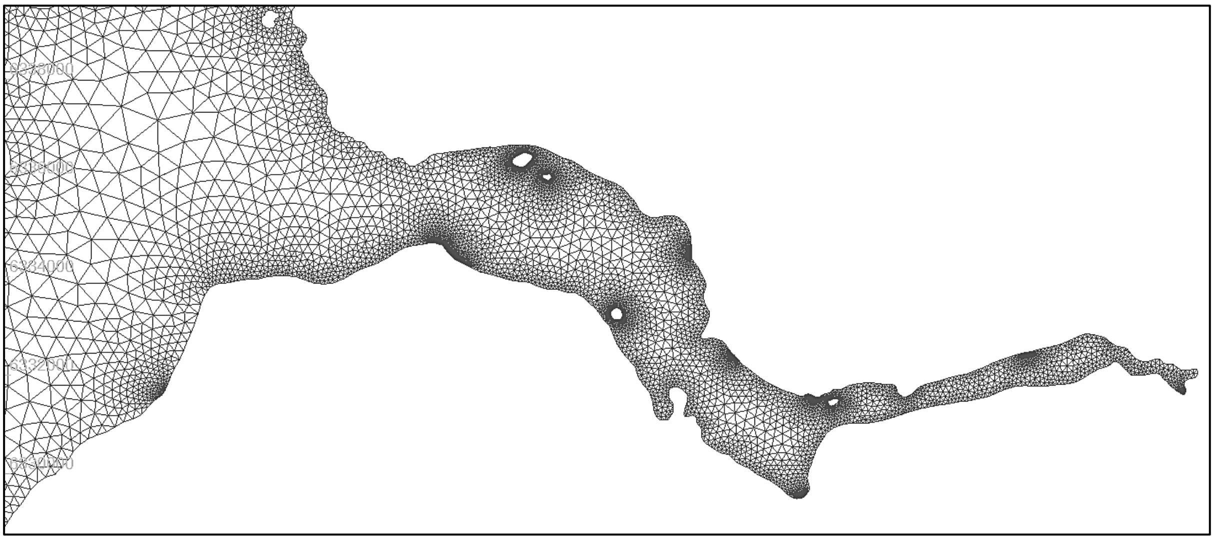


Figure 23 *Telemac refined mesh within Loch Hourn.*

The available bathymetry data is summarised in section 3.1. The model bathymetry was established by interpolating the bathymetry data onto the computational mesh.

3.3 *Offshore tidal boundary conditions*

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 *et al.*, 2002). Initial values of temperature and salinity were set to 8 ^{o}C and 34.5 PSU, respectively, and zero-gradient boundary conditions applied at the open sea boundaries.

3.4 *Meteorological forcing*

Winds can play an important role in the hydrography of the West Coast and the meteorological forcing data was taken from (Time and Date, 2021) as described in section 3.4.

3.5 *3D mesh resolution*

It is important that the model resolution adequately resolves the local flow structures and spatiotemporal patterns arising from interaction of tidal currents, bathymetry, and geography.

A notable feature of the West Coast bathymetry is the steep variations in the seabed; water depths increasing from less than 10m to more than 140 m depth across just a few hundred metres. Ten vertical mesh layers were selected to follow the meshing strategy of Sabatino *et al.,* (2016). Ultimately, there is a balance to be struck between levels of detail and computational run times.

3.6 *3D stratification effects*

The annual cycle of stratification along the West Coast of Scotland, due to a combination of solar heating and freshwater inflow, produces gradients in both temperature and salinity that induce flow circulation. These are three-dimensional phenomena that may be captured by employing a non-hydrostatic approach where the water density varies with both salinity and temperature. Thus, the effects of freshwater discharges into Loch Hourn, Loch Linnhe and the surrounding areas are taken into account in our model and the density is calculated according to the law of state for density as a function of temperature *T* (^{o}C) and salinity *S* (PSU):

$$\rho = \rho_{ref}\left[1 - \left(T\,(T - T_{ref})^2 - 750S\right)10^{-6}\right]$$

At fresh water inlets the salinity was kept constant in space and time with a value of $S = 0$ PSU applied. Following the work of Sabatino *et al.,* (2016), the river outflow temperatures were set to follow the air temperature and an average value (film temperature) between the local air temperature and an assumed sea temperature of 8 ^{o}C was employed.

Atmosphere-water heat exchange was included in the model using a first-order, lumped parameter approach (Sweers, 1976) according to:

$$k\frac{\partial T}{\partial z} = -\frac{A}{\rho C_p}\left(T - T_{air}\right)$$

The coefficient *A* includes for phenomena such as radiation, air convection in contact with water and latent heat produced by water evaporation. Sweers (1976) expresses the coefficient A, in W/m^2 / ^{o}C, according to the water temperature *T* and wind velocity *V* measured at the point under consideration (in m/s) according to:

$$A = (4.48 + 0.049T) + 2021.5b(1+V)(1.12 + 0.018T + 0.00158T^2)$$

The parameter *b* varies depending on location and a value of 0.002 was found appropriate for this study.

For turbulence closure the 2-equation *k-epsilon* turbulence model (Launder, 1974) was employed for both vertical and horizontal resolution.

4 Model Validation

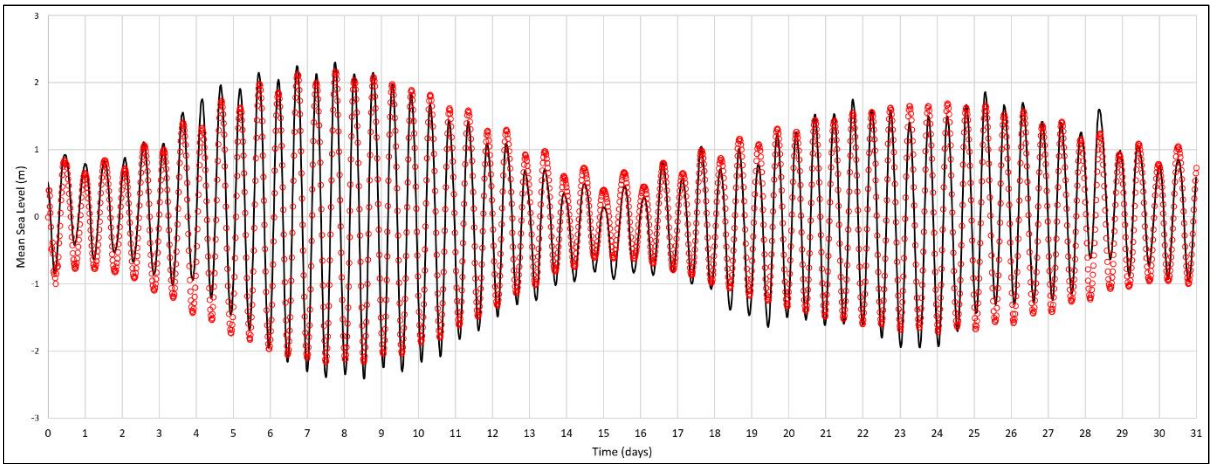
4.1 *Water level*

Validation is against observed hydrographic data in terms of sea levels and current speeds as described in sections 2.2 and 2.3.

This includes data from long-term sea level gauges operated by the British Oceanographic Data Centre (BODC), water ADCP current values from a flow meter located at the existing salmon farm on Loch Hourn and Marine Scotland observations in Loch Linnhe.

The model is observed to simulate the propagation of the tide within the general computational domain with satisfactory validation against recorded sea levels at the five different locations described in section 2.2 –*Tobermory, Loch Hourn, Ullapool, Stornoway and Kinlochbervie,* as shown in Figure 24.

(a)



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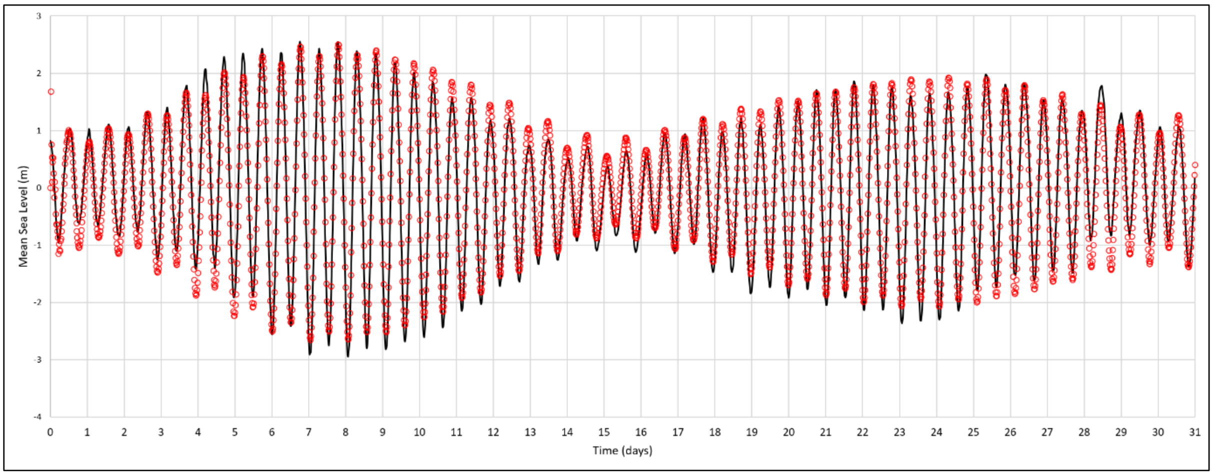

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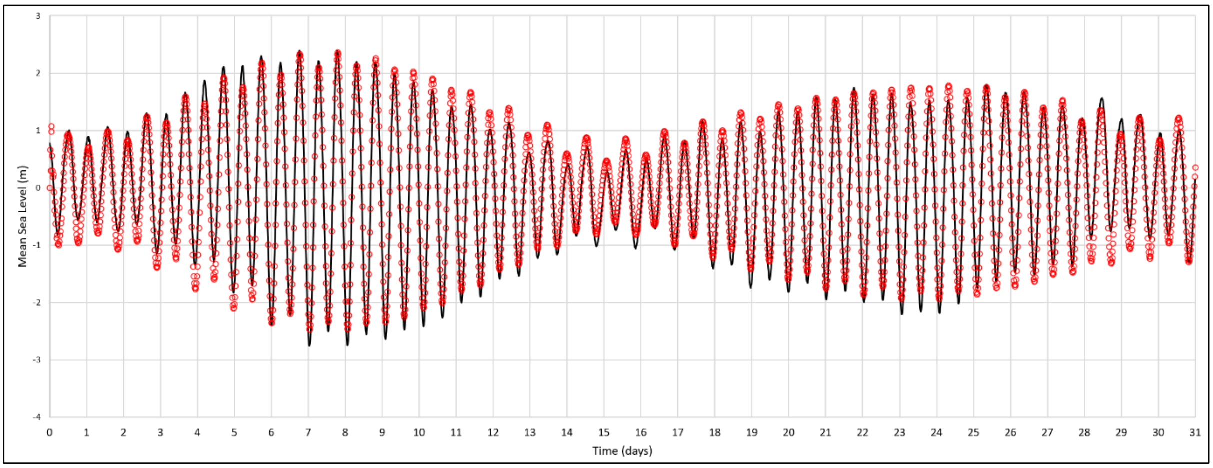

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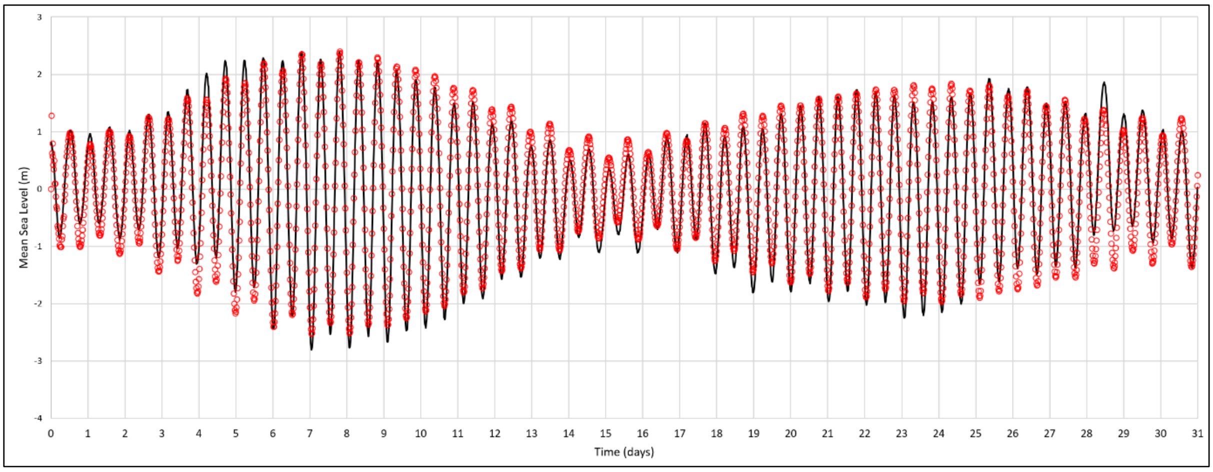

(e)

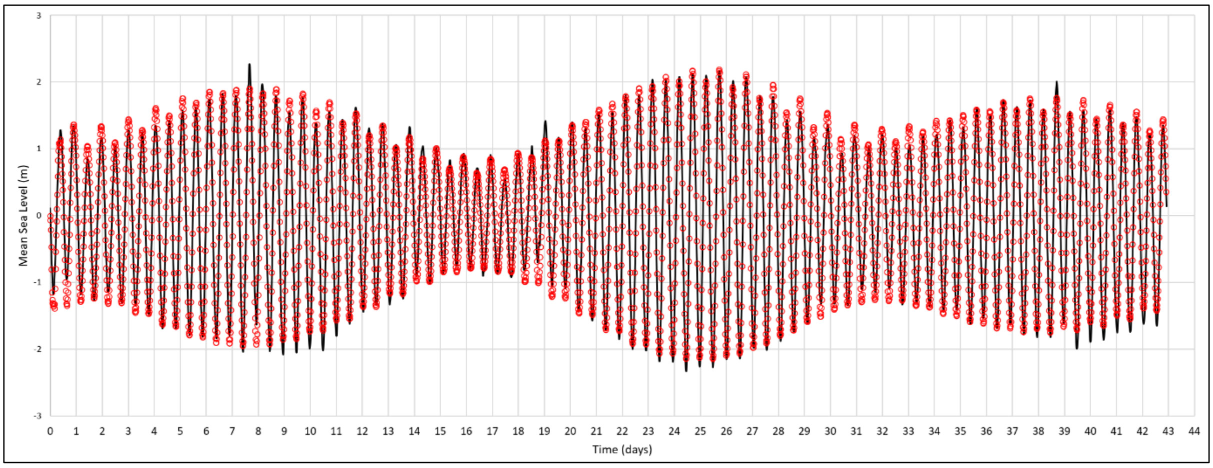

Figure 24 *Sea levels at (**a) Tobermory**, (**b) Ullapool**, (**c) Stornoway**, (**d) Kinlochbervie**, (**e) Loch Hourn**. **(a)-(d)** are for the period 1st – 31st October 2010. **(e)** is for the period 28th November 2018 – 11th January 2019. Solid line is the BODC data and line with symbols is the Telemac model. All data are relative to mean sea level (MSL).*

For Loch Linnhe, the tidal propagation at Fort William, South Loch Linnhe and Tobermory is shown in Figures 25 to 27.

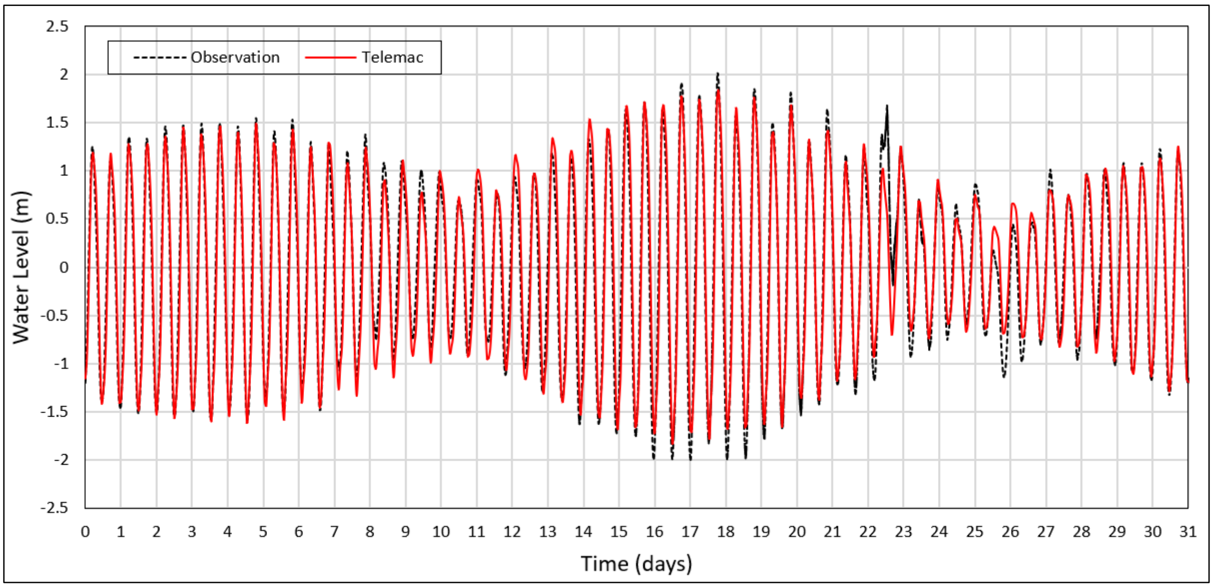

Figure 25 *Sea level at Fort William for the period 1st – 31st May 2011. All data are relative to mean sea level (MSL).*

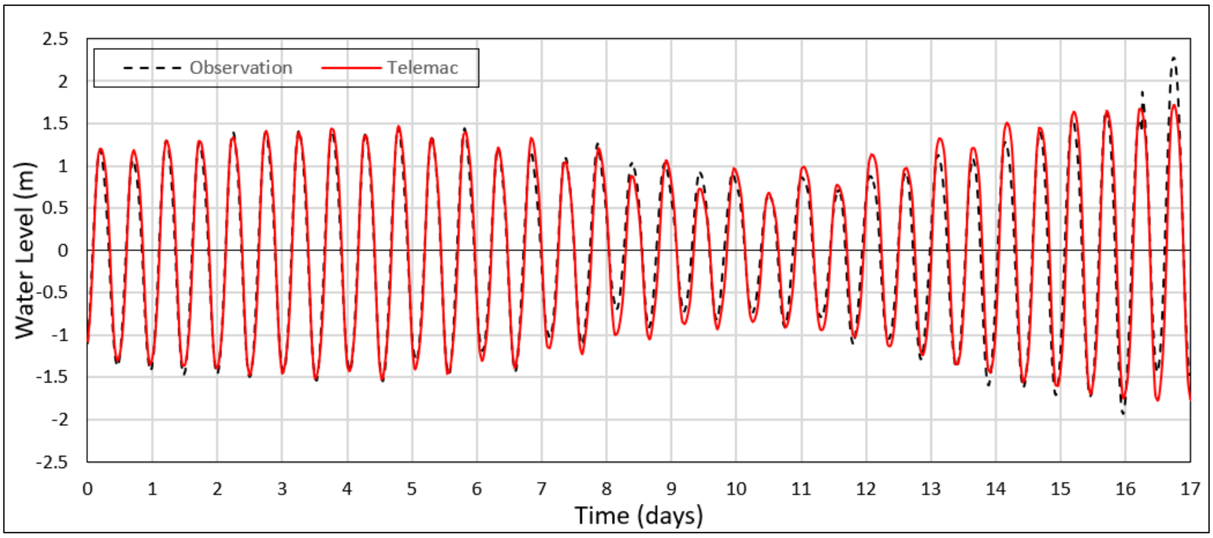

Figure 26 *Sea level at South Loch Linnhe (see Figure 11 for location) for the period 1st – 31st May 2011. All data are relative to mean sea level (MSL).*

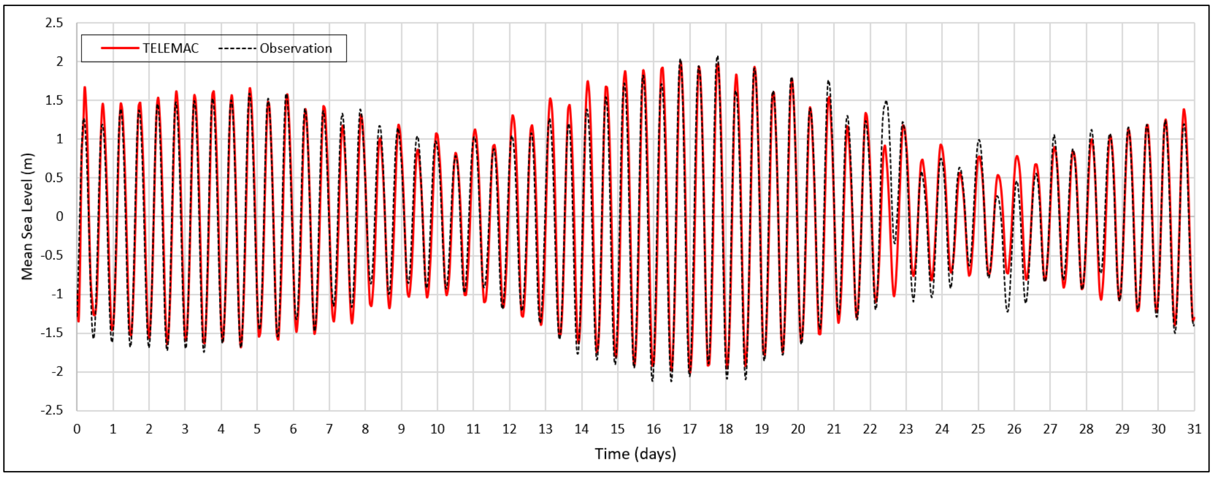

Figure 27 *Sea level at South Loch Linnhe (see Figure 11 for location) for the period 1st – 31st May 2011. All data are relative to mean sea level (MSL).*

In comparison with the physical data the root mean square errors (RSME) for Fort William and Tobermory were 0.260 *m* and 0.217 *m*, respectively. The tidal range is 2-4 *m* which produces an RSME relative to the tidal range of 6.7%-13.5% for Fort William and 5.4%-10.8% for Tobermory. These are within the bounds required by this type of modelling according to Environment Agency guidelines (SSM_4, 2015).

4.2 *Current speed and direction*

Focusing on the salmon farm at Loch Hourn, the predicted current speed magnitudes and directions are also in satisfactory agreement with observed data as shown in Figures 28 to 30.

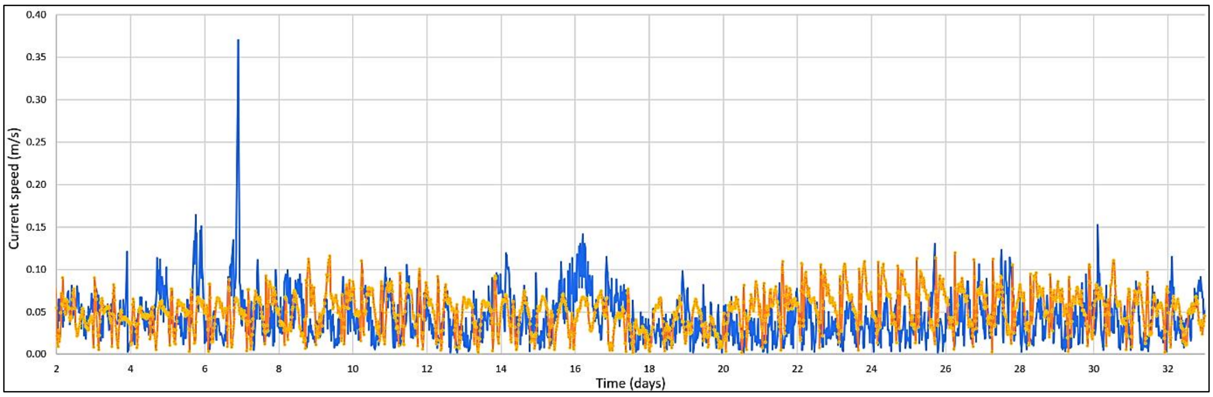

Figure 28 *Near-surface current speed magnitudes at the Loch Hourn salmon farm for the period 1st -30th December 2018. Blue lines are Mowi measured data and orange lines with symbols are the Telemac predictions.*

The average Telemac predicted value was 0.049 m/s while the average measured speed was 0.043 m/s giving confidence that the model is a reasonable representation of physical reality.

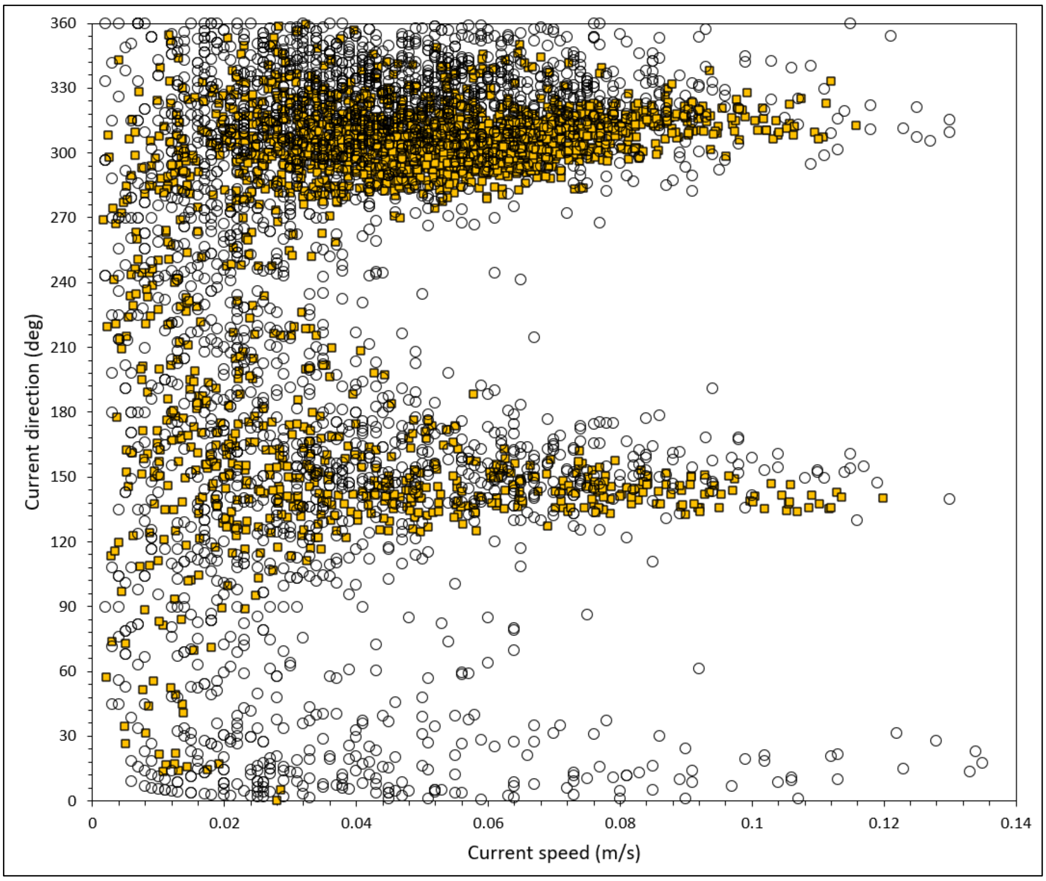

Figure 29 *Near-surface current speed magnitudes and directions for the salmon farm at Loch Hourn for the period 1st - 30th December 2018. Empty symbols are Mowi measured data, filled symbols are the model results.*

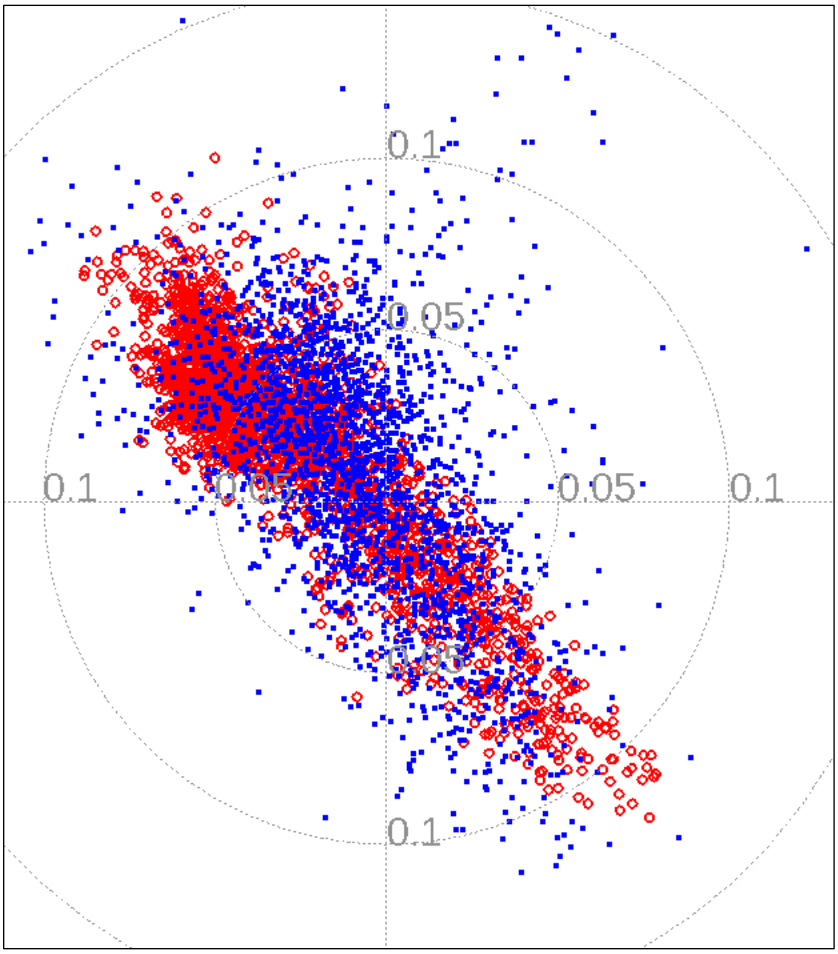

Figure 30 *Polar plot of near-surface current speed magnitudes and directions for the salmon farm at Loch Hourn for the period 1st - 30th December 2018. Filled square symbols are Mowi measured data, empty circle symbols are the Telemac model results.*

Figures 29 and 30 show that the principal current speed magnitudes and directions have been captured in a reasonable manner by the Telemac HD model at Loch Hourn.

With regard to the flows in Loch Linnhe, Figures 31 and 32 show the surface current speed and direction at the mid-Loch Linnhe locations shown in Figure 13. A reasonable quantitative concurrence between the model and physical data is found.

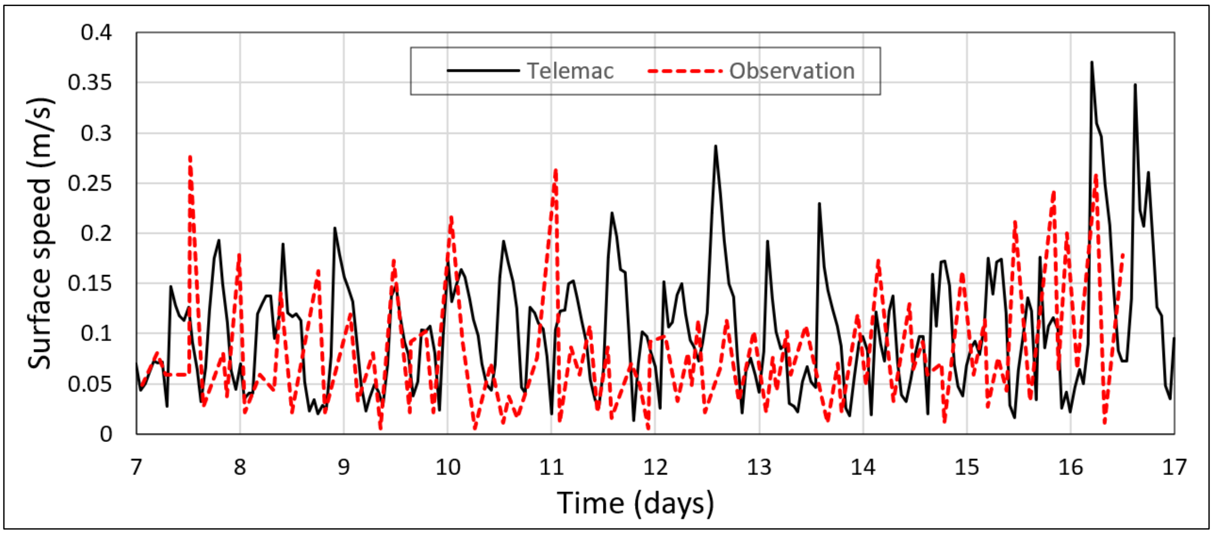

Figure 31 *Near-surface current speed magnitudes at the RDCP location at mid-Loch Linnhe (see Figure 13) for the period 7th -17th May 2011.*

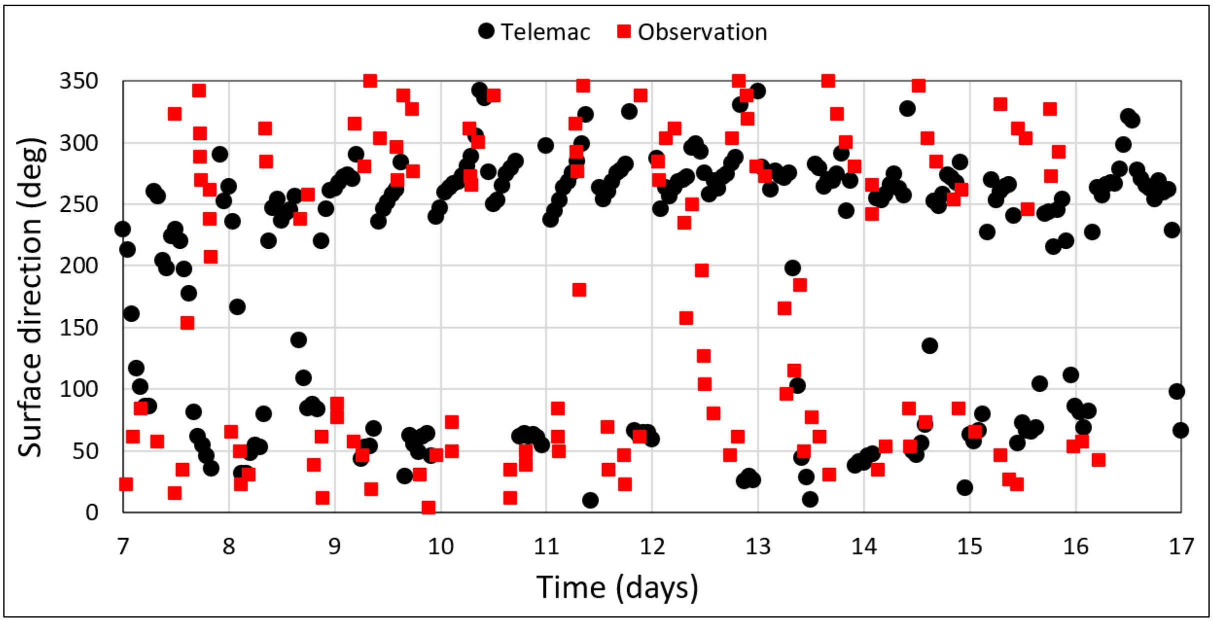

Figure 32 *Near-surface current speed directions at the RDCP location at mid-Loch Linnhe (see Figure 13) for the period 7th -17th May 2011.*

4.3 *Further model validation: general current features*

It has been observed (Simpson, 1986) that there exists a large-scale organised flow bifurcation near the Little Minch where a notable feature of the current was its interaction with the island chain of the Hebrides, as described in section 2.1. Observations suggested that on entering the Minch (the channel between Scotland and the islands), part of the flow turned westward, crossed the Minch and flowed southward along the Hebrides coast before turning northwards. This flow feature has been successfully captured by the Telemac model as shown in Figure 33. Neutrally buoyant particle tracers (black dots) were released into the model at a constant rate between Feb. 1st – March 27th 2019 from Lochs Alsh, Duich, Hourn and Nevis. Dispersion plots (A-F) show that the Telemac model has captured the general northward flow and the observed bifurcation in the region of the Little Minch where the flow turns southward and a clockwise circulation is generated around the islands including South Uist, Barra and Mingulay

Figure 3, shown previously, of the current speed vectors also shows the capture of this flow phenomenon.

These results give further confidence that the Telemac model is predicting recognized physical features of the hydrography of the West Coast seascape.

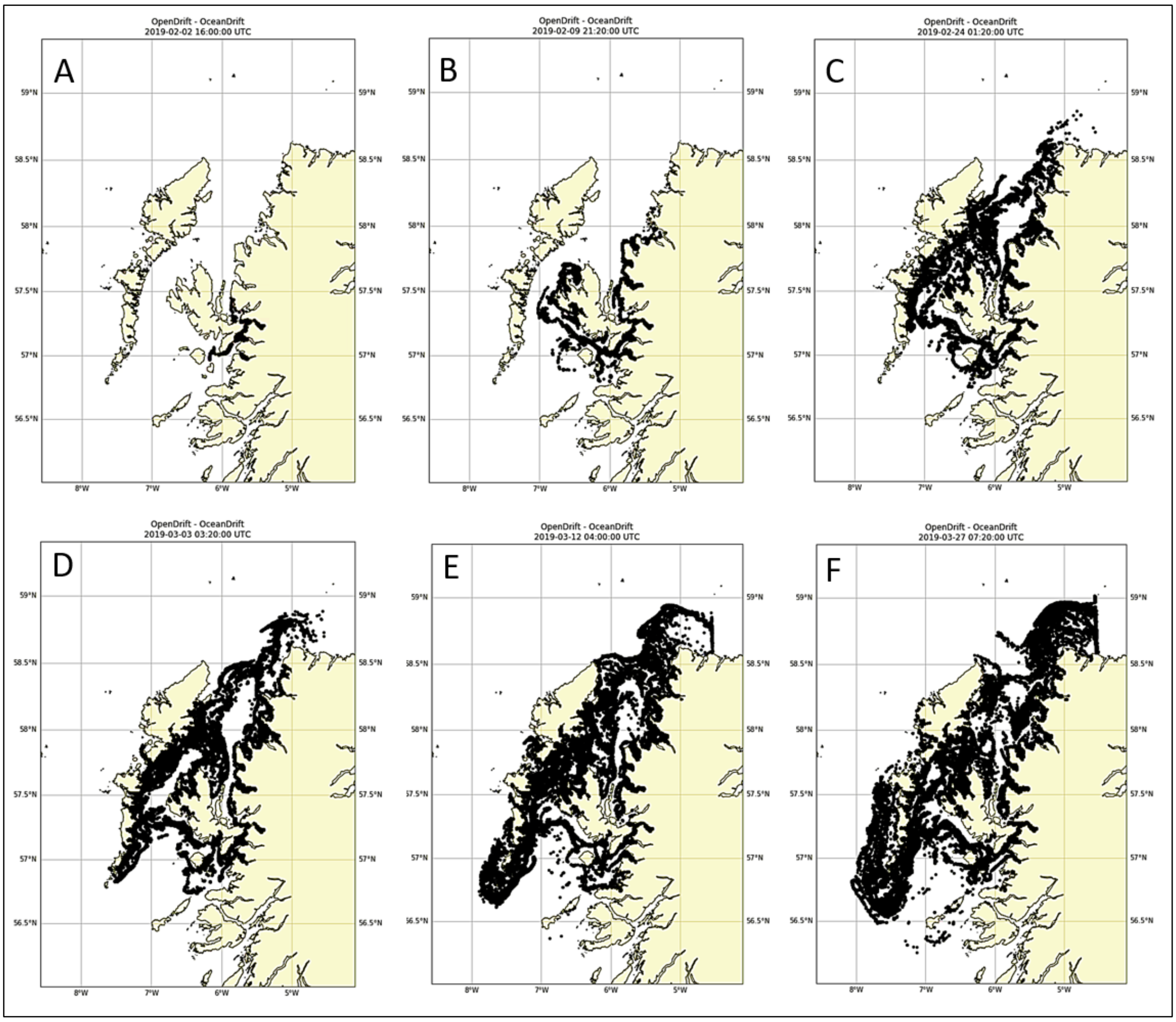

Figure 33 *Particle tracers (black dots) released between Feb. 1st – March 27th 2019 from Lochs Alsh, Duich, Hourn and Nevis. Dispersion plots (A-F) show that the Telemac model has captured the general northward flow and the observed bifurcation in the region of the Little Minch where a clockwise circulation is generated around South Uist, Barra and Mingulay.*

4.4 *Further model validation: salinity comparisons*

The methodology for the Telemac procedure in the Loch Hourn model was to begin with a 3-month (89-days) “spin-up” calculation from 1st Feb. to 30th April 2019. This allows fields of velocity, salinity and temperature to develop in the model.

Information on the salinity field in Loch Hourn were provided by (Mowi, 2021) as shown previously in Figure 3.6. The Telemac predictions of the salinity field are shown in Figures 34 to 36.

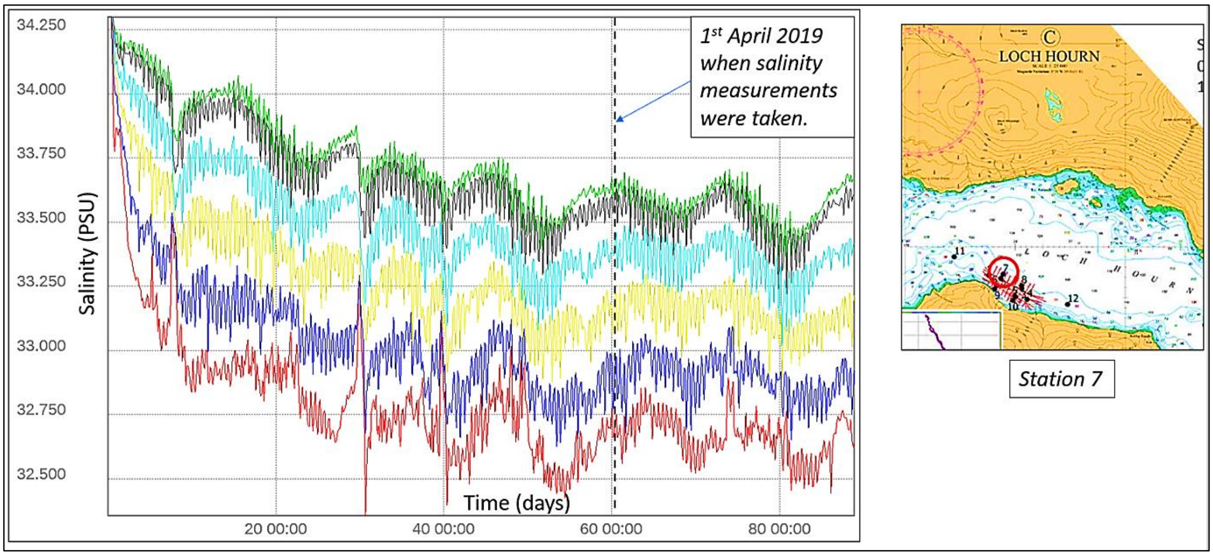

Figure 34 *Telemac hydrodynamic model salinity at* ***Station 7*** *over the 89 day “spin-up” period from 1st Feb. – 30th April 2019. Plot shows freshwater dilution of initially saline sea water (34.3 PSU). Colour represent different depths – red near surface, green near sea-bed.*

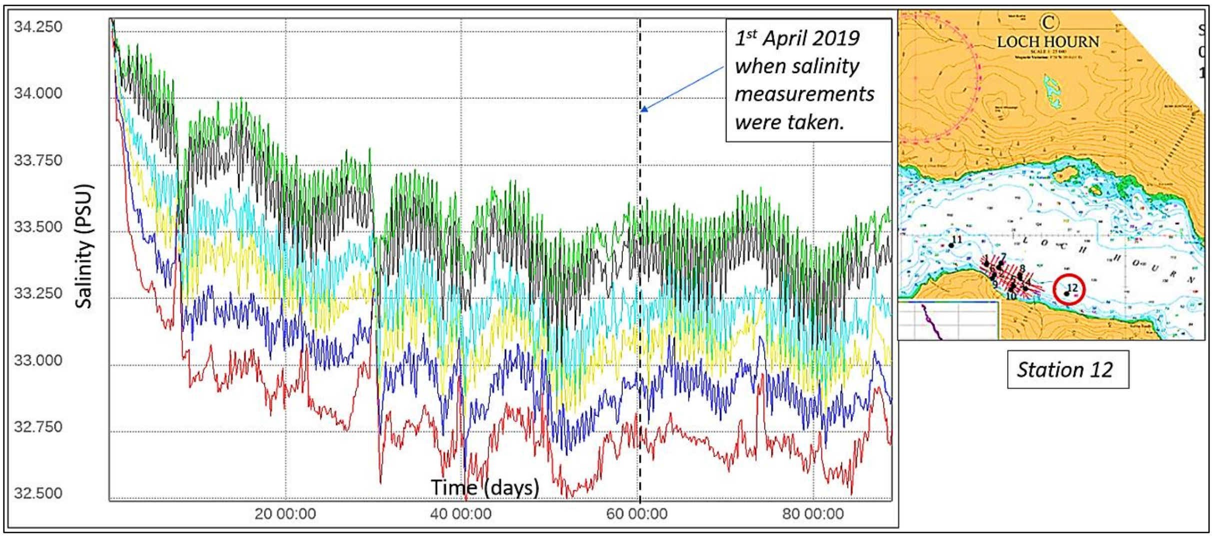

Figure 35 *Telemac hydrodynamic model salinity at* ***Station 12*** *over the 89 day “spin-up” period from 1st Feb. – 30th April 2019. Plot shows freshwater dilution of initially saline sea water (34.3 PSU). Colour represent different depths – red near surface, green near sea-bed.*

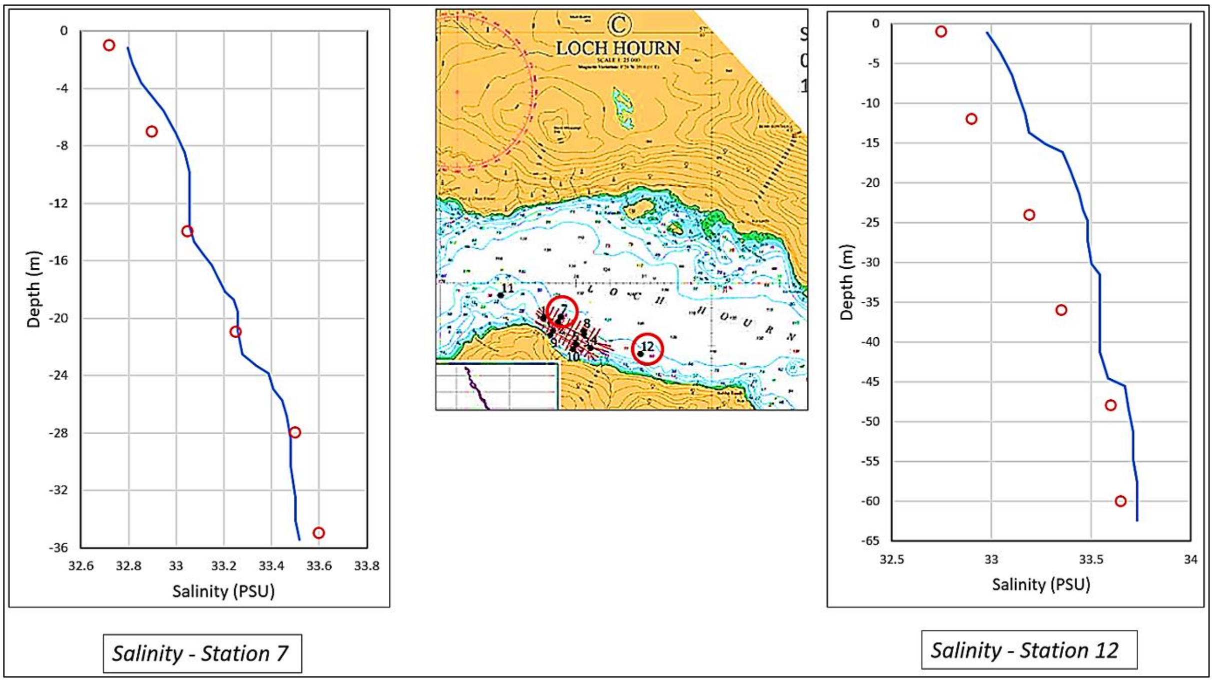

Figure 36 *Telemac hydrodynamic model salinity versus depth at stations 7 and 12. Lines are Mowi measured data, symbols are the Telemac model predictions. Model data was extracted on 1st April 2019.*

Figures 34 and 35 show the hydrodynamic model salinity predictions over an 89-day period from 1st February to 30th April 2019. The predictions show how initially saline water at 34.3 PSU is diluted by freshwater discharging into Loch Hourn. Figure 36 shows the Telemac model results for salinity with depth at stations 7 and 12. Although the Telemac model data was extracted on 1st April 2019 it is not anticipated that significant differences will exist in the overall salinity fields compared with the Mowi measurements that were taken on 1st April 2021. Figure 36 demonstrates that the Telemac model predictions for salinity appear to be in reasonable agreement with the measured Mowi data.

For the Loch Linnhe model with 85 freshwater inlets, the spin-up period was 1-month from 1st-30th April 2011. Figure 37 shows the near-surface salinity profile versus time for the data buoy location shown in Figure 17 at upper Loch Linnhe. Both the Scottish Shelf Model (SSM_4, 2015) and the Telemac models capture reasonably well the salinity evolution with the Telemac model performing well after 20-days when the river Lochy at Fort William was subject to significant flow rates exceeding 200 m^3/s.

Vertical profiles of salinity show satisfactory agreement with observation as shown in Figure 38 for the two locations at mid-Loch Linnhe shown in Figure 18.

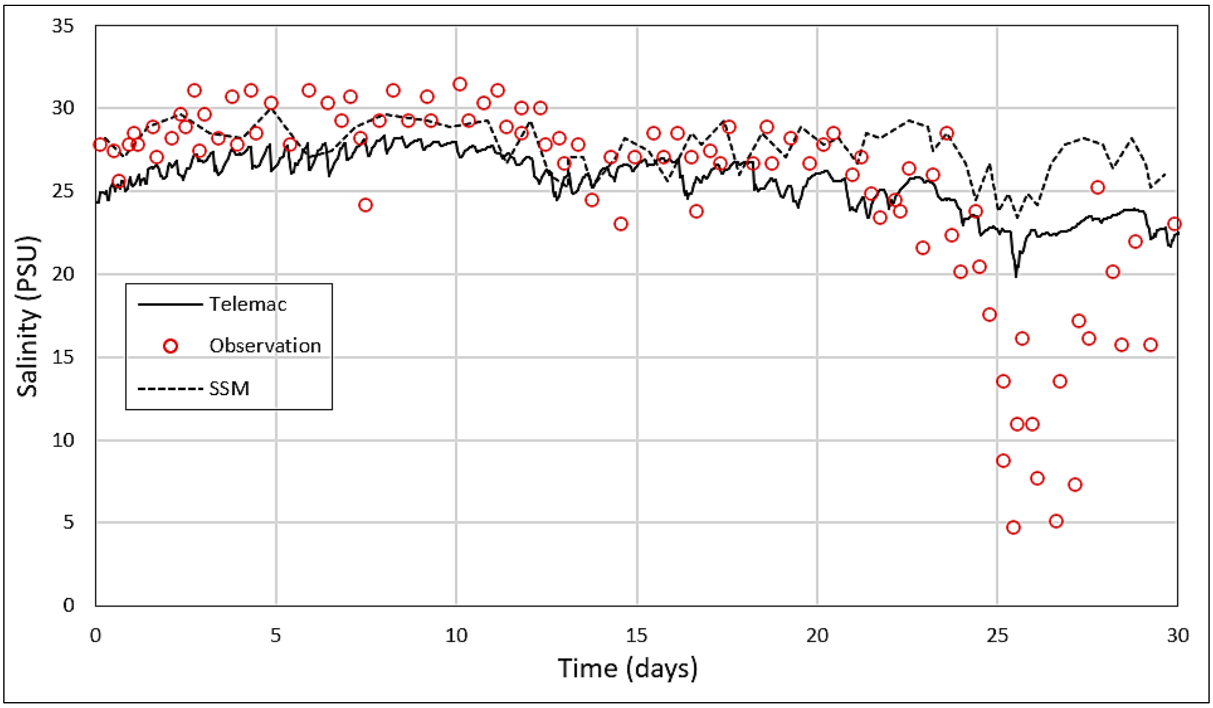

Figure 37 *Telemac and Scottish Shelf Model (SSM) near-surface salinity predictions versus time for the period 1st – 30th May 2011.*

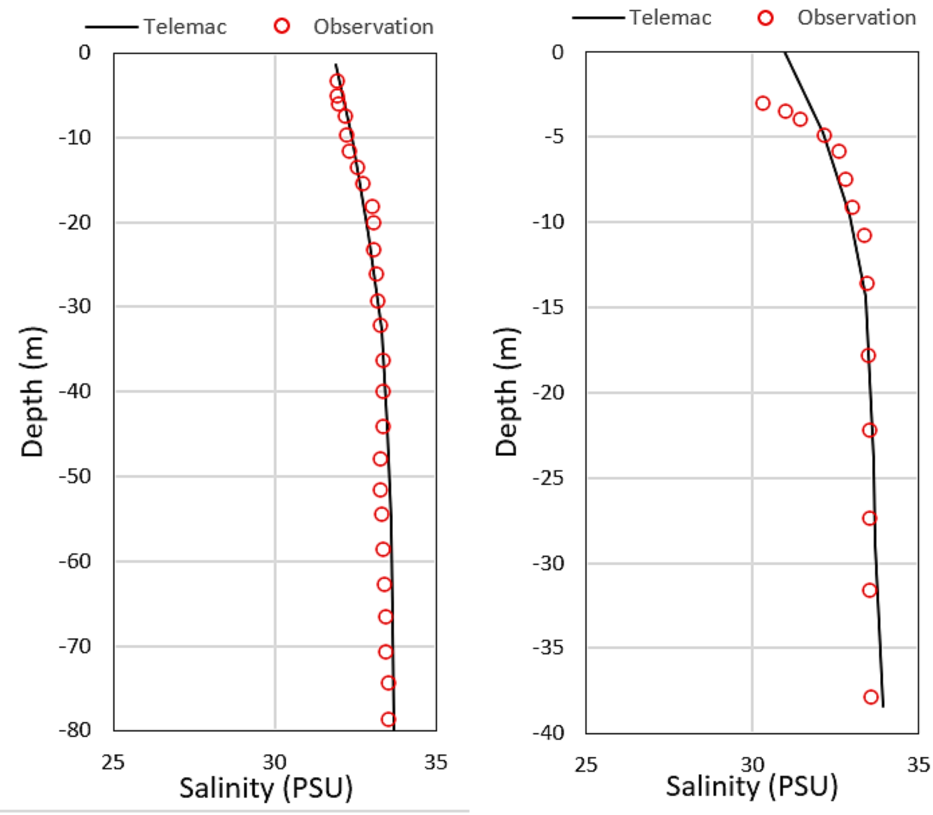

Figure 38 *Telemac salinity predictions versus depth at mid-Loch Linnhe on the 14th May 2011. The graph on the left corresponds to the left-hand location in Figure 18 and vice-versa for the right-hand image.*

4.5 *Further model validation: temperature comparisons*

Information on the temperature field in Loch Hourn were provided by (Mowi, 2021) and were shown previously in Figure 16. The Telemac hydrodynamic model sea temperature predictions at **Station 7** over 89 days from 1st Feb. – 30th April 2019 are highlighted in Figure 39. This plot shows effects of atmosphere-water heat exchange on sea water initially at 8 ^{o}C. The final hydrodynamic model predictions lie in the range of 7.25 to 7.5 ^{o}C while the Mowi measured values were approximately 7.3 ^{o}C. Although the model and measured values were taken in different years (2019 and 2021, respectively), the magnitudes appear to be in reasonable concurrence.

Figure 40 shows the near-surface temperature profile versus time for the data buoy location shown in Figure 17 at upper Loch Linnhe. Both the Scottish Shelf Model (SSM_4, 2015) and the Telemac models capture the temporal evolution in a satisfactory manner.

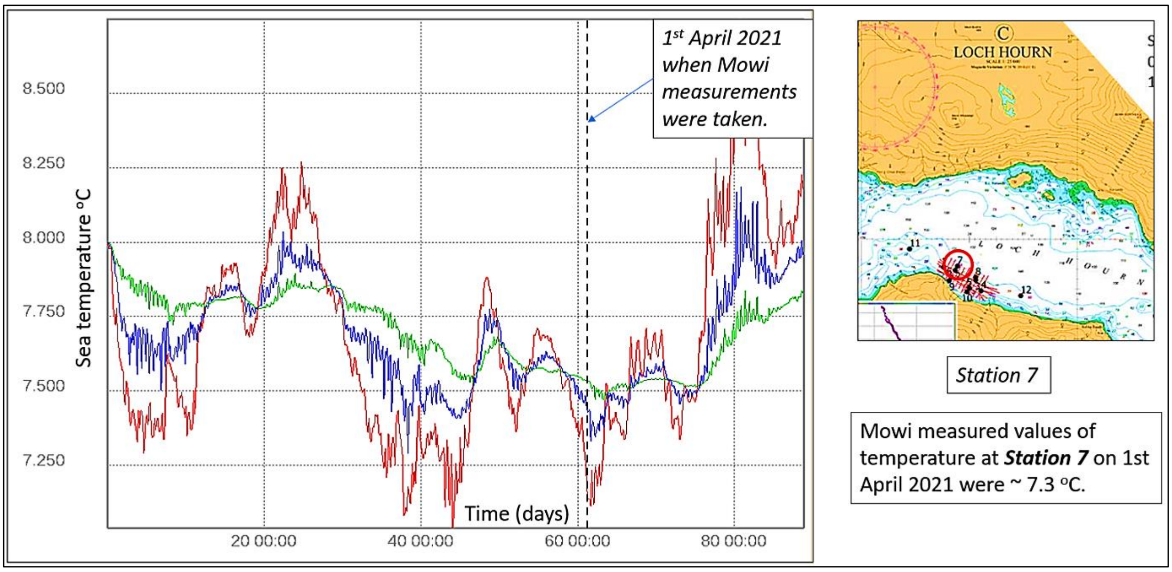

Figure 39 *Telemac hydrodynamic model sea temperature predictions in Loch Hourn at **Station 7** over the 89 day "spin-up" period from 1st Feb. – 30th April 2019. Plot shows influence of solar radiation, air temperature and evaporation on sea water initially at 8 °C. Colour represent different depths – red near surface, green near sea-bed.*

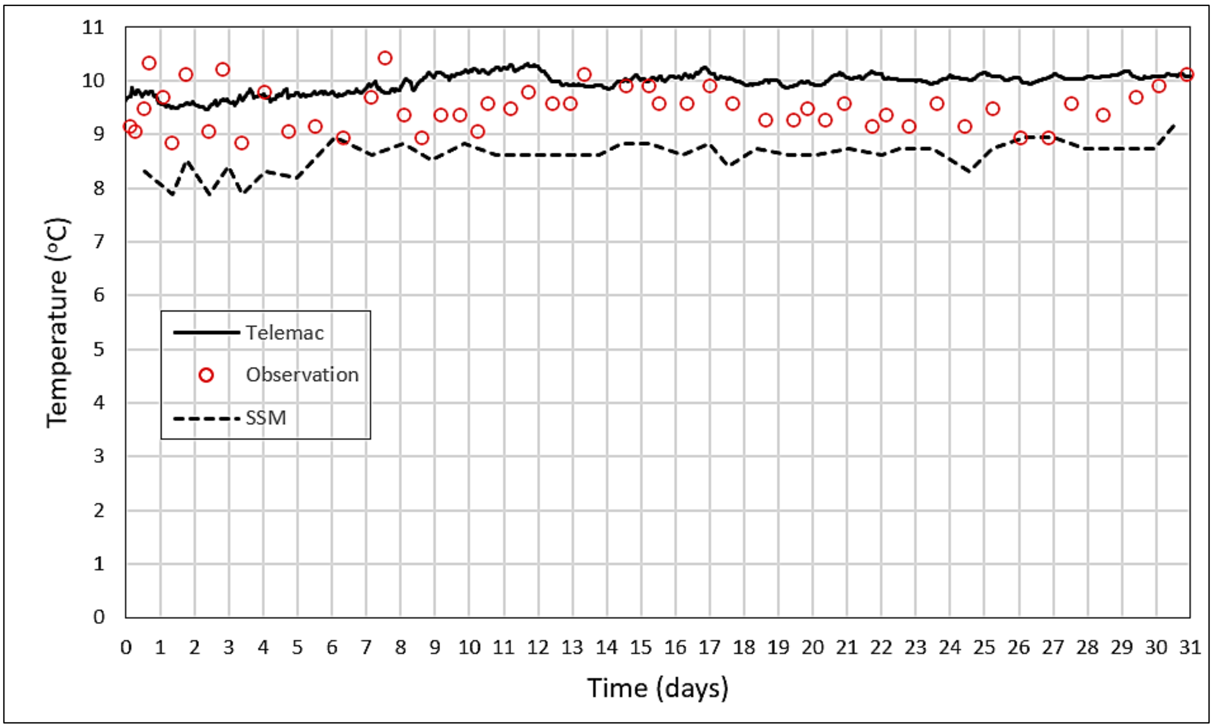

Figure 40 *Telemac and Scottish Shelf Model (SSM) near-surface temperature predictions versus time at upper Loch Linnhe for the period 1st – 30th May 2011.*

4.6 *Further model validation: average current speed comparisons*

Figure 41 shows the comparison of average current speeds for Telemac model and the Scottish Shelf Model (SSM)/NOC Atlas of Marine Energy Resources (SSM_2, 2021). The Telemac average data is for May-June 2019. Satisfactory qualitative and quantitative concurrence is found between the data sets giving confidence that the Telemac model predictions are a reasonable representation of physical reality.

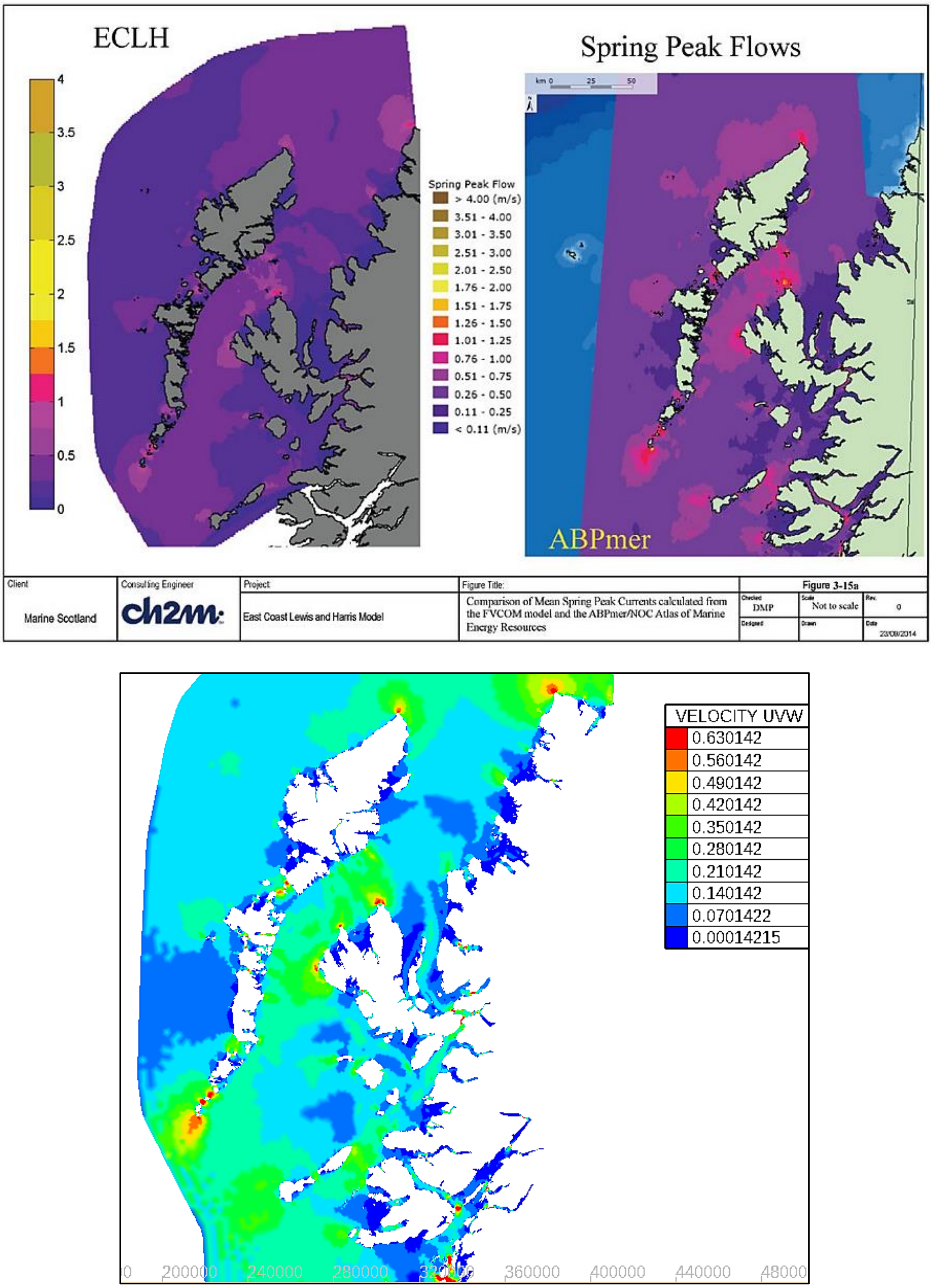

Figure 41 *Comparison of average current speeds for Telemac model (lower) and the Scottish Shelf Model (SSM)/NOC Atlas of Marine Energy Resources (upper) (SSM_2, 2021). Telemac average data is for May-June 2019. Satisfactory qualitative and quantitative concurrence is found between the data sets.*

5 Sample Results

5.1 *Hydrodynamics*

Figures 42 to 45 demonstrate the typical flow fields predicted by the Telemac model at the end of the 3 month "*spin-up*" period for the Loch Hourn study. This is followed by examples of salinity and temperatures contours across the West Coast model predicted by the Telemac hydrodynamics Loch Hourn model as shown in Figures 46 to 49.

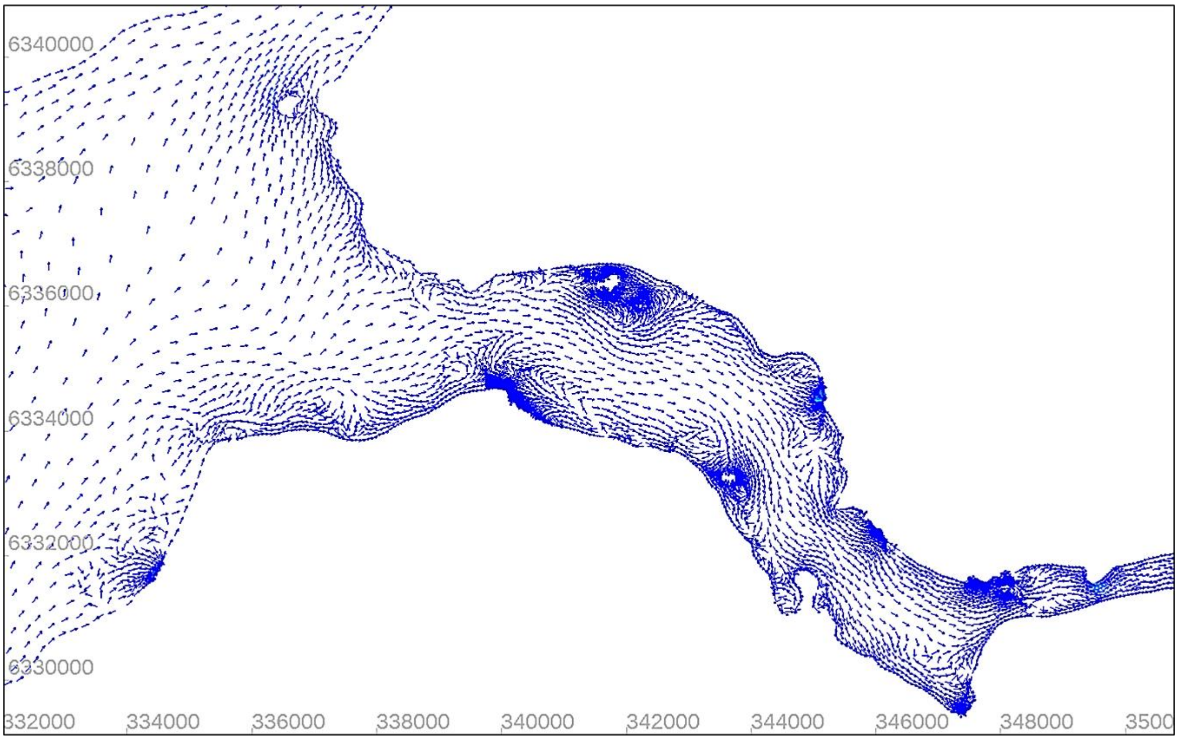

Figure 42 *An example of **near-surface** current speed vectors in Loch Hourn on a **flood tide**. Flow field is a complex interaction of the competing effects of tides, winds, freshwater discharge, density stratification, bathymetry, coastal and island topography and Earth spin.*

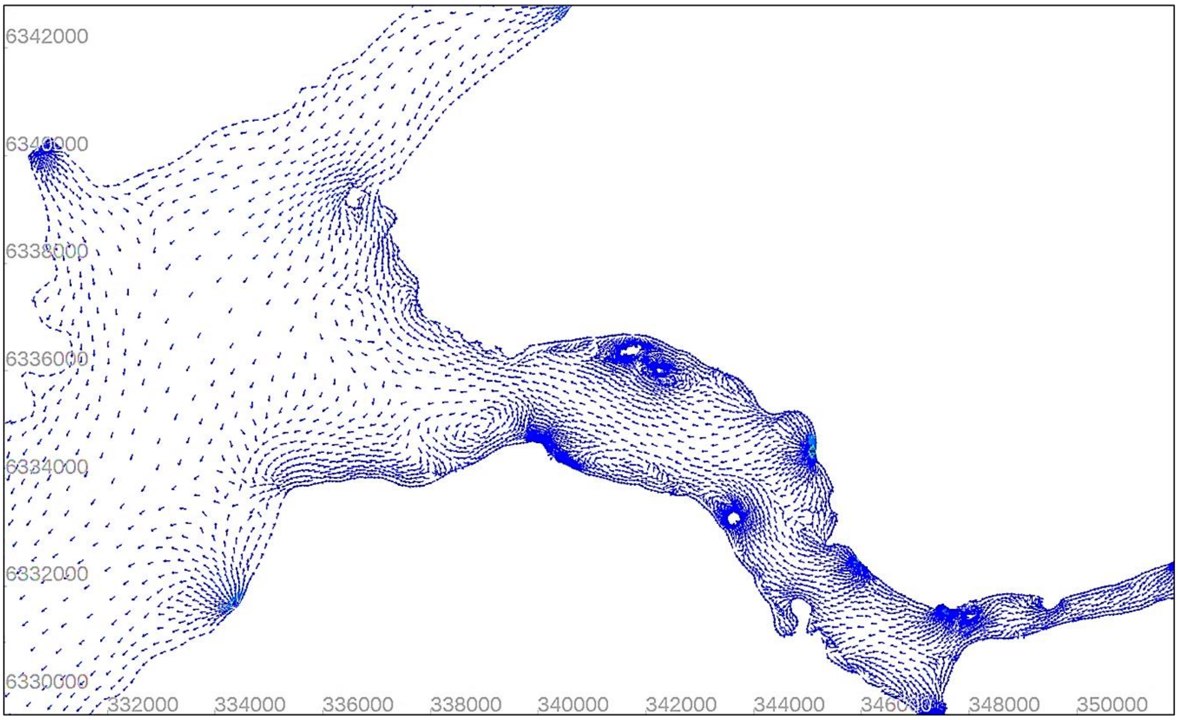

Figure 43 *An example of* ***near-surface*** *current speed vectors in Loch Hourn on an* ***ebb tide****. Flow field is a complex interaction of the competing effects of tides, winds, freshwater discharge, density stratification, bathymetry, coastal and island topography and Earth spin.*

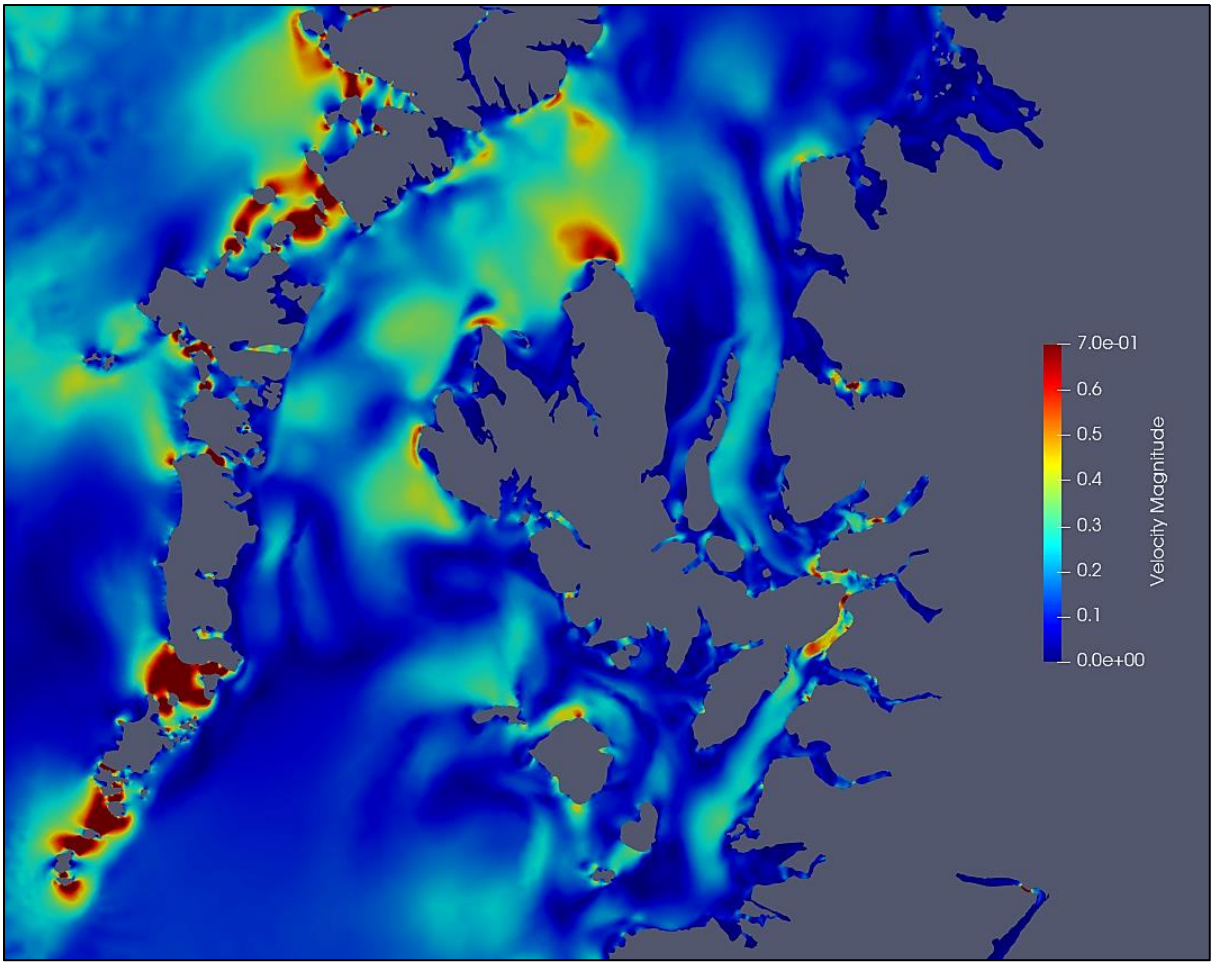

Figure 44 *Example snapshot of current speed magnitude (m/s) in the North West Coast regional seas. Larger flow speeds are evident at coastal headlands, in the channels between islands and in Loch Alsh and the Kyle Rhea.*

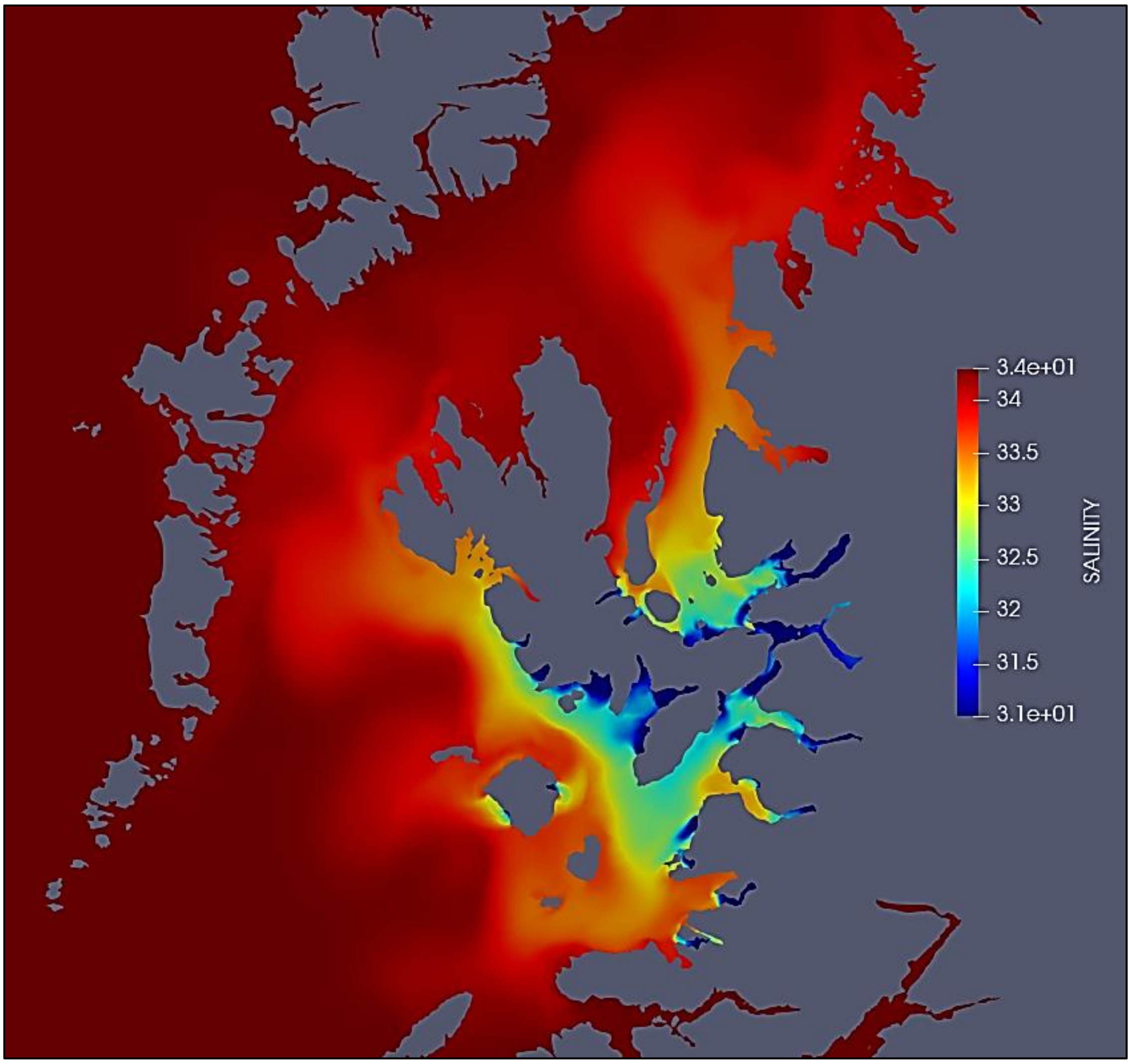

Figure 45 *Post "spin-up" snapshot of **near-surface** salinity contours (PSU) in the North West Coast regional seas on 1st May 2019 for the Loch Hourn model. Freshwater discharge is ONLY from the 40 river inlet locations shown in Figure 14.*

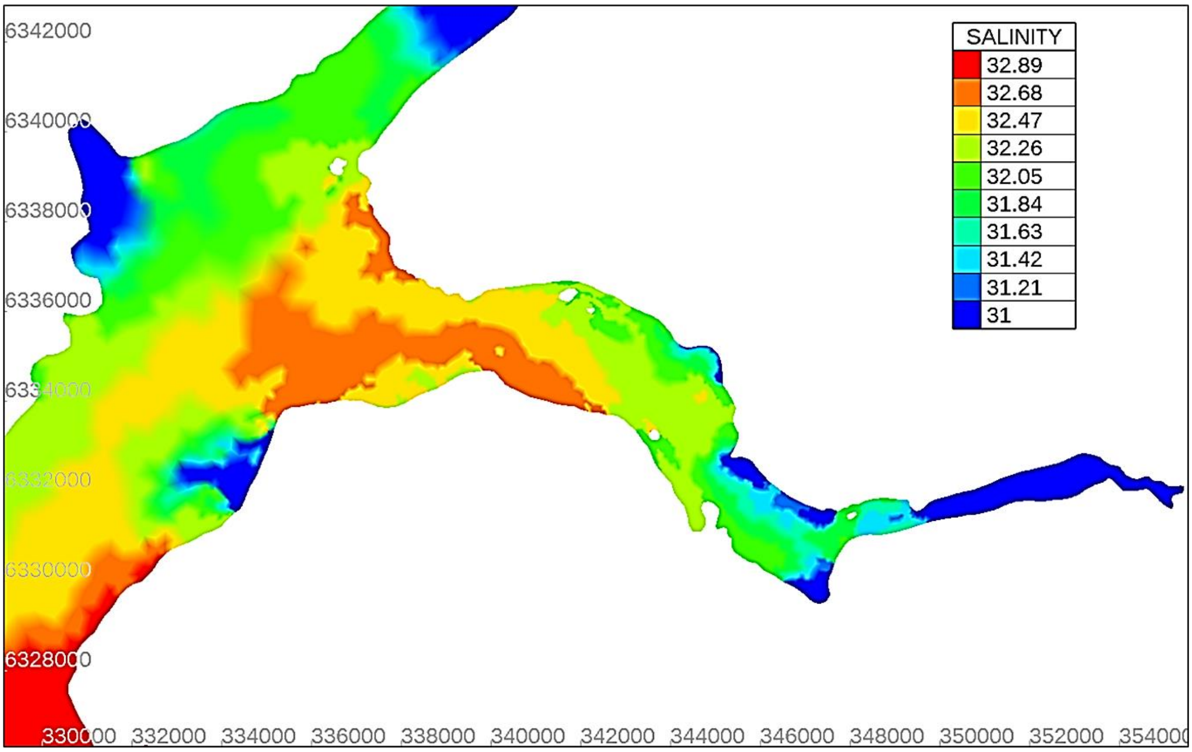

Figure 46 *Snapshot of **near-surface** salinity (PSU)in Loch Hourn to highlight density stratification.*

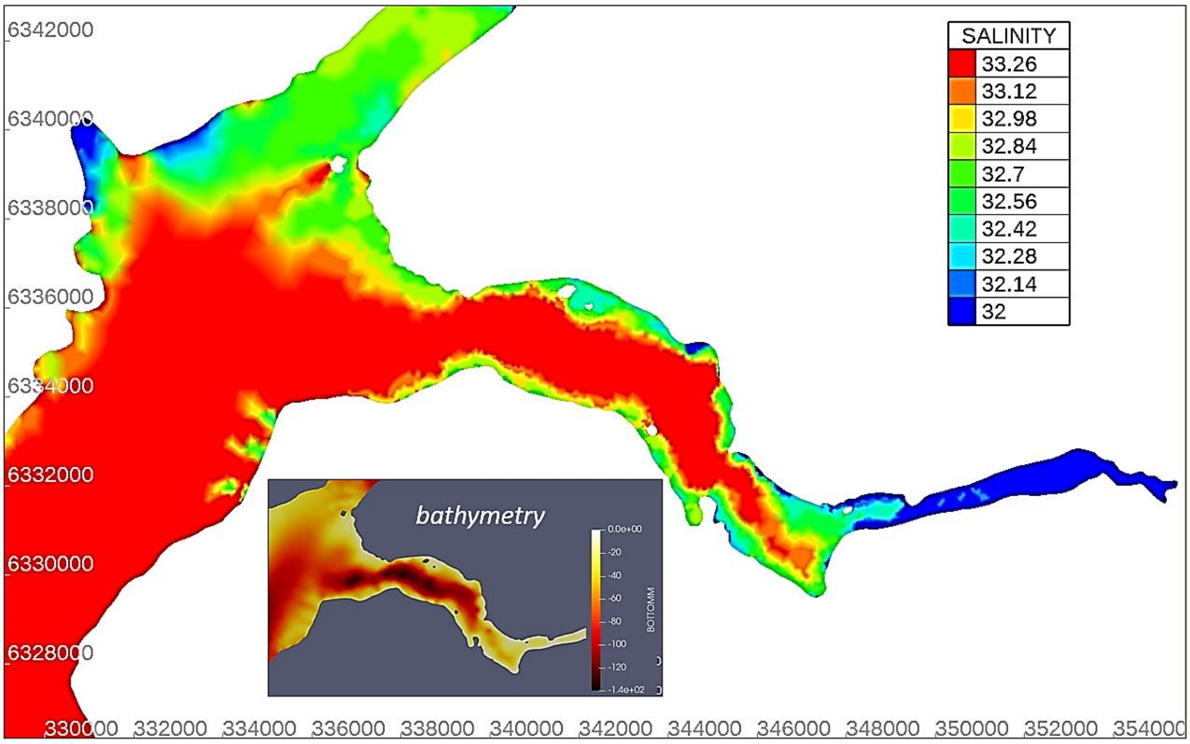

Figure 47 *Snapshot of **mid-depth** salinity (PSU) in Loch Hourn to highlight density stratification. Denser, more saline water resides in deeper sea-bed canyons. Increased salinity levels closely shadow deeper bathymetry (m) contours - see insert.*

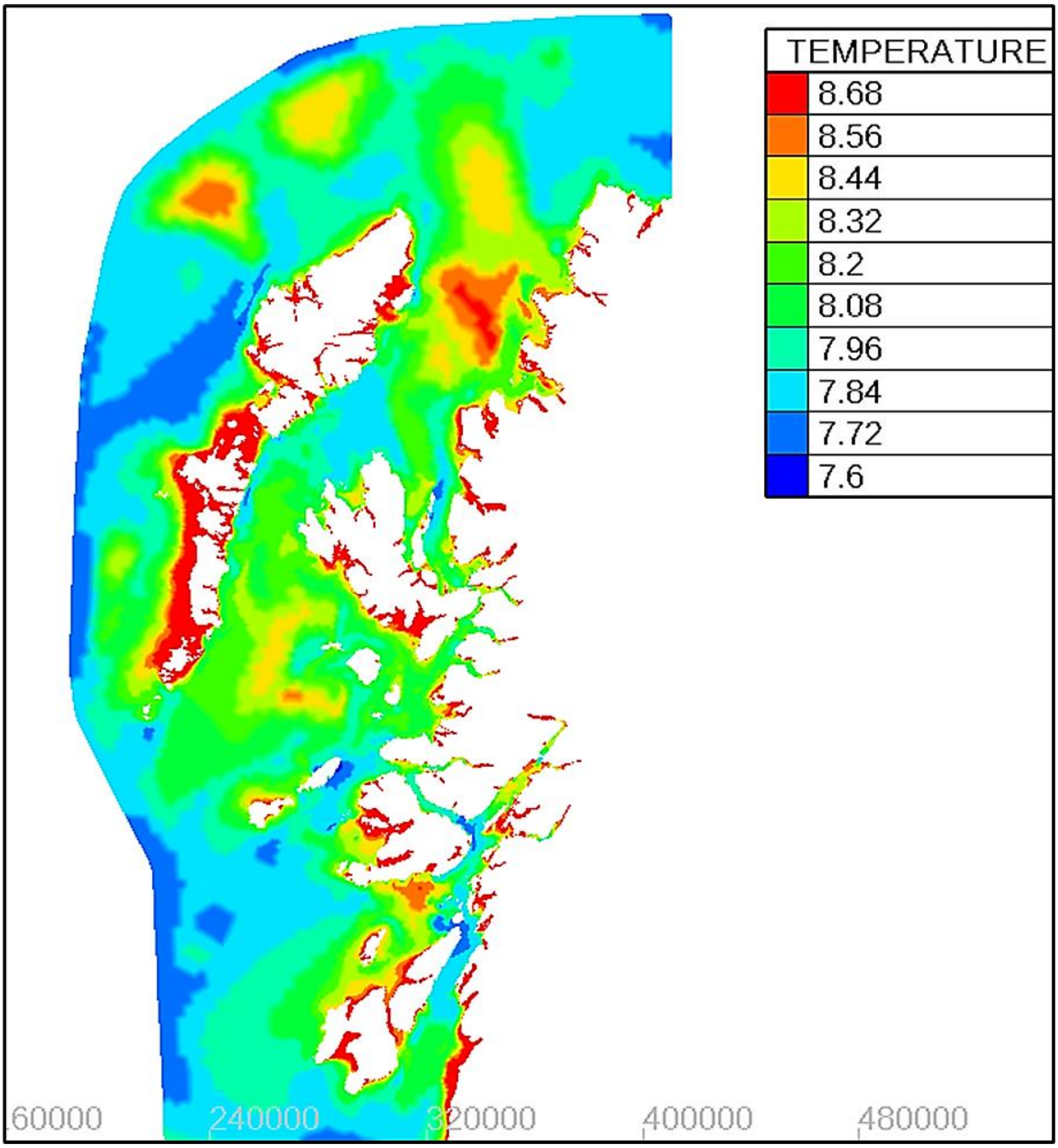

Figure 48 *Post "spin-up" snapshot of* ***near-surface*** *temperature (°C) contours across the West Coast regional seas on 1st May 2019.*

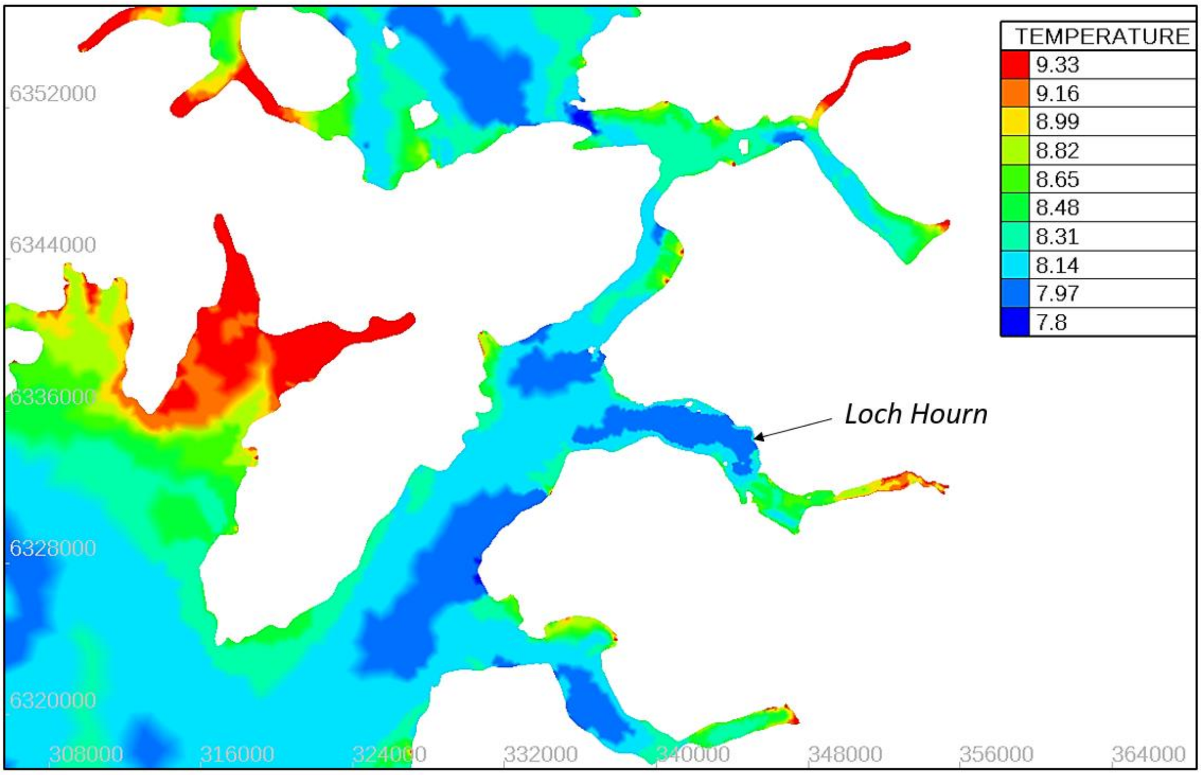

Figure 49 *Post "spin-up" snapshot of* ***near-surface*** *temperature (^oC) contours in the Loch Hourn region on 1st May 2019.*

For the Loch Linnhe model Figures 50 and 51 show snapshots of the surface salinity and temperature fields on the 31st May 2011.

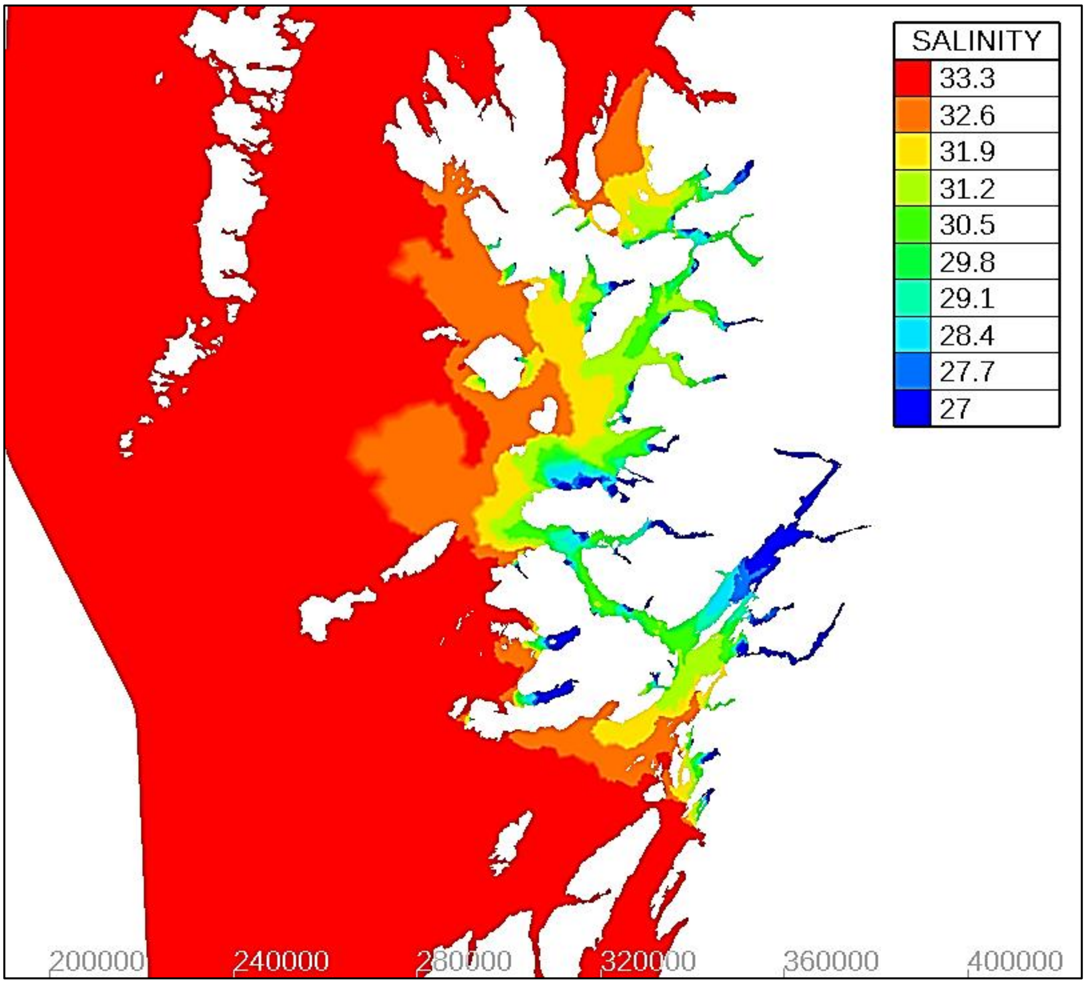

Figure 50 *Snapshot of* ***near-surface*** *salinity contours (PSU) in the North West Coast regional seas on the 31st May 2011 for the Loch Linnhe model. Freshwater discharge is from the 85 river discharge locations shown in Figure 15.*

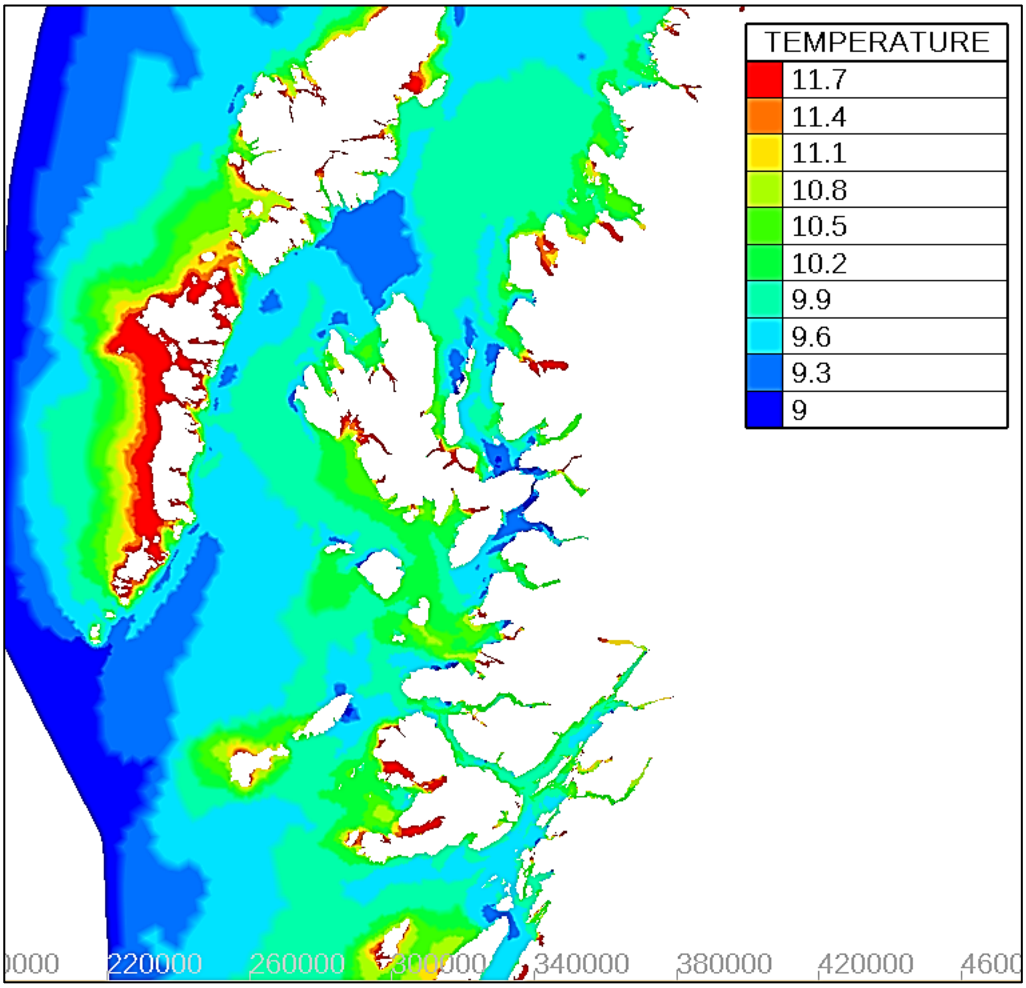

Figure 51 *Snapshot of **near-surface** temperature (°C) contours across the West Coast regional seas on 31st May 2011 from the Loch Linnhe model (85 rivers).*

5 Discussion of hydrodynamic and sea lice model results

Sections 2, 3 and 4 of this report described the construction, methodology and validation of a 3D hydrodynamic model of the West Coast of Scotland focusing on the flow patterns in Loch Hourn and Loch Linnhe. Model validation was performed against observed water levels, current speeds, salinity and temperature measurements. The focus of the model validation was to assess the model capabilities of predicting current speed and current direction in Loch Hourn and Loch Linnhe as well as the general water circulation in the West Coast region. This was to support ongoing studies for the assessment of the near-field and far-field impacts of the proposed and existing West Coast salmon farms on the water environment with respect to sea lice pressure on wild fish and pesticide dispersion.

Tidal energy is input to the West Coast seas from the North Channel of the Irish Sea and the western Atlantic. The Telemac hydrodynamic model provided a satisfactory prediction of the propagation of the tidal effects throughout the west coast as evident from the prediction of water levels at various locations across the envelope of the model. ADCP current meter magnitude and direction measurements in Loch Hourn and Loch Linnhe were predicted to be in good agreement with physical data.

The model includes the effects of wind forcing on sea movements. A second important factor to consider is that the 3D HD model for this study assumes non-hydrostatic conditions (i.e., non-constant water density). Seas off the West Coast represent an area of complex water circulation exhibiting varying levels of density stratification throughout the year. These are three-dimensional phenomena, the effects of which can only be fully captured with a varying water density model such as the one employed here.

Overall, it has been established that the Telemac hydrodynamic model can capture the dynamics of the water levels and current circulation within the West Coast seas and into Loch Hourn and Loch Linnhe. This offers insight into the spatial and temporal variation in the flow environment around the West Coast of Scotland and other localities including the islands. The hydrodynamic model provides a suitable basis for modelling sea lice and pesticide dispersion in both the near- and far-fields.

6 Conclusions

- To support sea lice and pesticide dispersion studies and their impact on marine environment, the Coastal Communities Network (CCN) has commissioned the development of a 3D hydrodynamic (HD) model of the West Coast of Scotland. The model simulates water levels and flows (i.e., currents and tides) at spatial and temporal scales not possible from direct measurements.
- The HD model correctly simulates the propagation of the tide within West Coast and provides an overall reasonable description of the general circulation within Loch Hourn and Loch Linnhe in terms of the current magnitude, direction, salinity and temperature.
- The HD model includes the effects of complex water circulation, density and temperature gradients that persist in the West Coast seas throughout the year. These three-dimensional phenomena appear to be adequately captured in the 3D HD model.
- The HD model provides a suitable data basis for modelling sea lice and pesticide dispersion on the West Coast.

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