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A Hydrodynamic Model of the West Coast of Scotland with Coupled Sea Lice Dispersion

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Abstract— **In order to assess the risk that wild salmon and sea trout will be harmed by parasitic sea lice emanating salmon farms a three-dimensional hydrodynamic and biological model of the West Coast of Scotland has been developed. The model uses TELEMAC-3D-WAQTEL and the computational 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 model was successfully validated against observed hydrographic data (water levels and currents) and was found to provide a reasonable description of salinity and temperature levels. In an integrated biological model, virtual particles were constructed within the framework of the open-source particle-tracking code OpenDrift. These were released at each farm site and allowed to disperse into the marine environment. Each particle is a "super-individual", representing a number of sea lice larvae. The biological effects of sea lice production, maturity and mortality rates, salinity avoidance, temperature preference and phototactic vertical swimming behaviour (diel migration) were included. Results show that infective lice copepodids accumulate along tidal and salinity fronts, at the mouths of sea lochs and along shorelines, in different places according to the neap/spring tidal cycle and provide an indication of infestation risk to migrating wild fish.**

I. INTRODUCTION

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. Farmed salmon are hosts for parasitic sea lice which are proven to harm wild salmon and sea trout [1, 2]. The risk of infestation by sea lice varies according to the density of lice to which the fish are exposed and the duration of that exposure [1, 3]. The wild salmon smolt migration may take place across a period of two months, but individual fish are likely to take only a few days to travel through local lochs to the open sea, so sea lice densities averaged over two months do not best represent the risk they face. In this paper the model outputs are presented in two ways, to demonstrate how the lice density and therefore the apparent risk vary:

1. Infective lice (copepodid) densities averaged over a 15-day period in May/June 2019 - a typical year when four of the seven modelled farms in this study contain high fish biomasses, shown as a heat map.
2. Copepodid densities calculated every hour, and converted to an equivalent daily lice density, shown as an animated series of lice density plots. These are the peak levels that migrating fish are likely to encounter. During their migration journey through the coastal area, they may pass through multiple areas of high lice density.

The oceanography of the west coast of Scotland, including the focus of this paper, Loch Hourn, 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 area were included to model salinity and temperature differences that act as an important driving force for fluid movement in fjordic systems such as those found on the West Coast. The influence of meteorological wind forcing and atmosphere-water heat exchange on the sea environment was also included for the time of year of the study. The modules employed were TELEMAC-3D-WAQTEL version v8p2. Coupled to the TELEMAC hydrodynamics results is a biological sea lice model, developed within the framework of the open-source particle tracking code OpenDrift [4].

II. GEOGRAPHIC AND HYDRODYNAMIC SETTING

A. *General topography and flow features*

North-west Scotland is notable for its complex topography and coastline. Glaciation has formed a great number of islands and peninsulas, while many sounds and fjords 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 [5]. Fig. 1 shows the regional location with the red inset showing the area of focus around Loch Hourn.

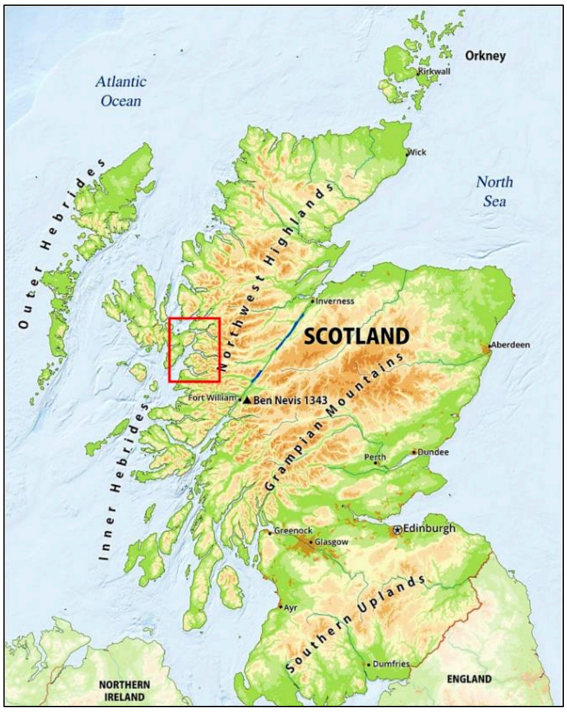

Figure 1. Geographical location with area of focus around Loch Hourn shown in red inset.

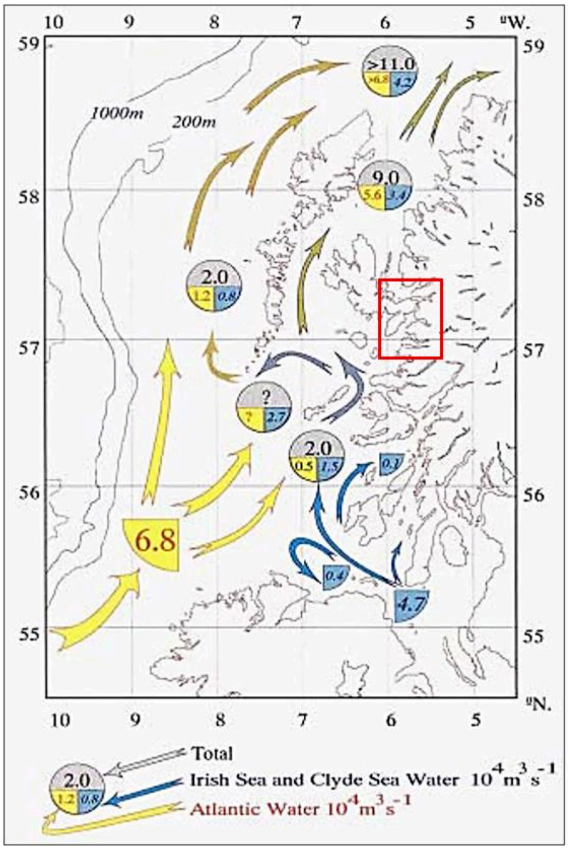

Figure 2. West Coast of Scotland general circulation patterns and approximate volume fluxes [6]. Area of focus around Loch Hourn shown in red inset.

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 [6]. Overall circulation patterns (Fig. 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). Flows within the waters closer to coasts and in sea lochs generally represent an arena 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.

III. AVAILABLE DATA

A. *Bathymetry data*

The bathymetry data for the present study have been collected from a range of different sources including publicly available data sets. These have been provided by Marine Scotland for the Scottish Shelf Model [7], digitised Admiralty charts and bathymetry information from the UK's Digimap

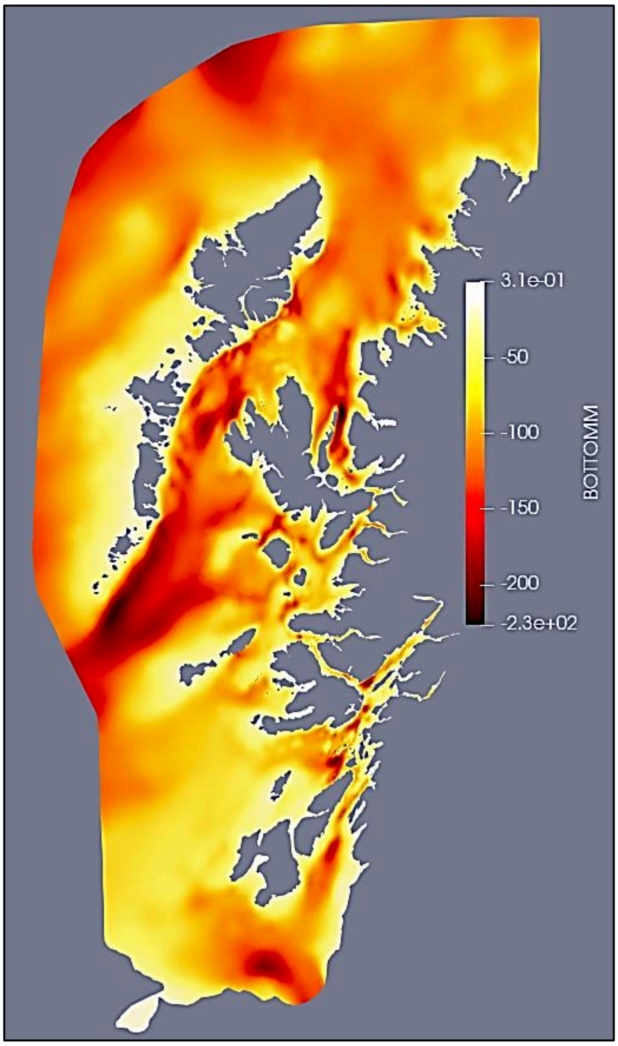

Figure 3. Model bathymetry (m) and spatial extent.

Ordnance Survey Collection [8]. The bathymetry and spatial extent of the model is shown in Fig. 3 while Fig. 4 shows the 3D bathymetry in the vicinity of Loch Hourn.

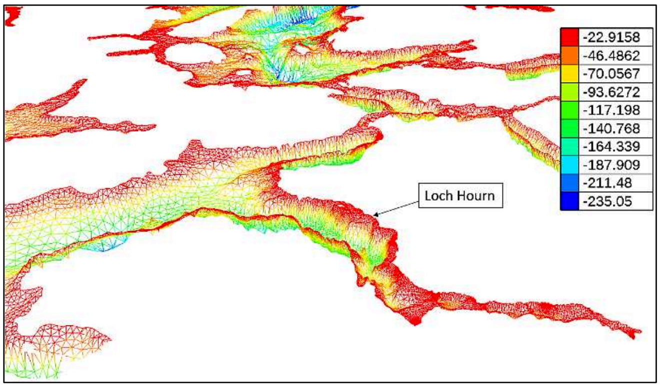

Figure 4. 3D model bathymetry (m) in the vicinity of Loch Hourn.

B. Sea levels

Data from the UK Tide Gauge Network is made available through the British Oceanographic Data Centre [9] who have responsibility for the monitoring and retrieval of sea level data.

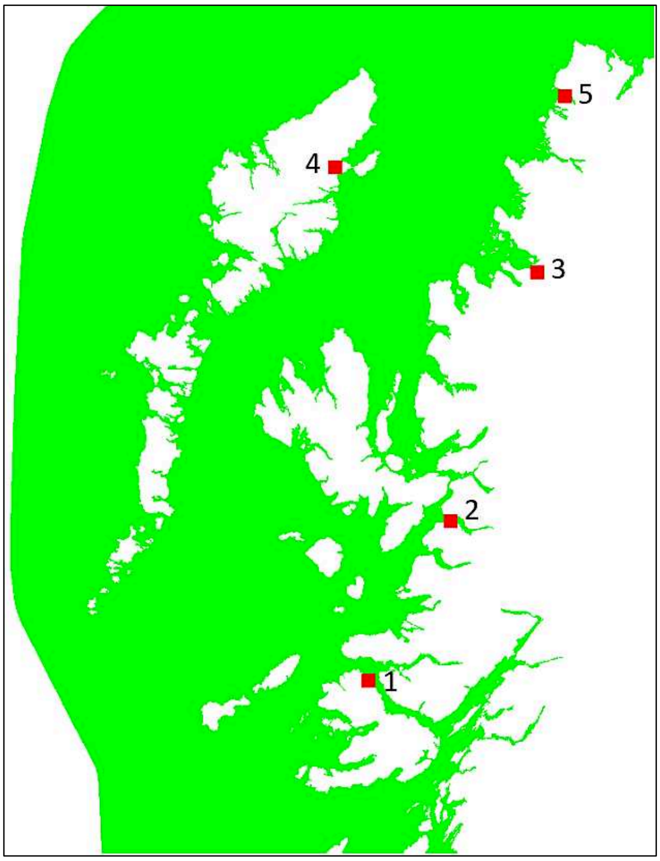

Figure 5. Map showing location of tidal gauge stations.

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

The data were extracted from stations 1,3,4 and 5 as shown in Fig. 5 for the period 1st – 31st October 2010. Sea level data were also provided by the aquaculture company Mowi at the Loch Hourn salmon farm for the period 28th November 2018 to the 11th January 2019.

C. Currents

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

D. Wind speed and direction

Wind speed and direction were extracted from an on-line resource [10]. The historical data are available on a six-hourly average basis and the wind data correlated with the time duration of the model. Wind speed and direction data were extracted at 3 wind station locations across the envelope of the model, these being at Port Ellen, Mallaig and Cape Wrath. Data information between each station was interpolated on to the model.

E. Freshwater sources

Data for freshwater sources (i.e., river run off) entering Loch Hourn and the surrounding area were extracted from the historical flow estimates from the network of hydrometric stations operated by the Scottish Environmental Protection

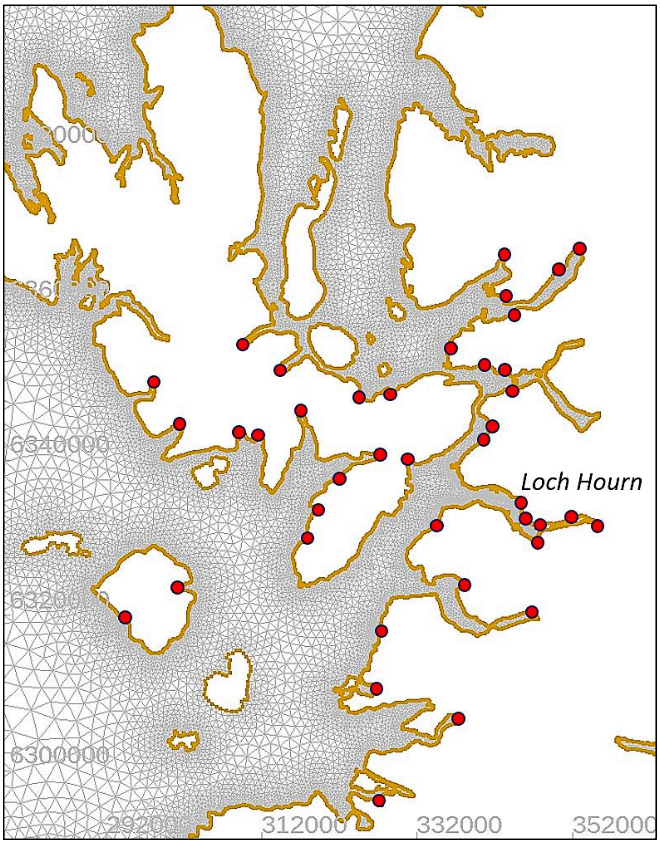

Figure 6. Map showing location of 40 freshwater discharges and the location of Loch Hourn.

Agency (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 [11]. Fig. 6 shows the location of the 40 freshwater discharge locations around Loch Hourn and the surrounding area that were included in the hydrodynamic model.

F. *Salinity and temperature*

Information on the salinity and temperature fields in Loch Hourn were provided by Mowi at locations close to the salmon farm. This data was used as a resource to allow validation of the TELEMAC-3D hydrodynamic model results

IV. MESHING AND MODEL SET-UP

A. *Model domain*

The domain of the TELEMAC-3D-WAQTEL model was shown in Fig. 3. 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.

The model contains two open (sea) boundaries 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 and down 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).

B. *Computational mesh*

The computational mesh was constructed using a flexible mesh approach with a varying spatial resolution (i.e., element length) across the domain (Fig. 7). Mesh resolution was down to 3 km at open sea boundaries and a few tens of metres at river inlets. Mesh generation was carried out using the freely-available BlueKenue code [12] and there were a total of 672,090 nodes and 991,820 elements in mesh. Six vertical terrain-following sigma layers were employed to account for the sea depth.

C. *Open sea boundary conditions*

The boundary conditions for the velocities and surface elevations at the offshore open boundaries were obtained from the OSU TPXO8 European Shelf regional model (11 tidal constituents: M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4) [13]. Initial values of temperature and salinity were set to 8 °C and 34.3 PSU, respectively, and zero-gradient boundary conditions applied at the open sea boundaries.

D. *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. A non-hydrostatic approach was adopted as the bathymetry in Loch Hourn can vary from shallow sills to deep canyons of around 200 m in the presence of salinity and temperature gradients. Explicitly including the z-velocity was considered appropriate to capture any 3D effects in such conditions. A hydrostatic approach was not considered. Thus, the effects of freshwater discharges into Loch Hourn and the surrounding area 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 (°C) and salinity S (PSU)[14]:

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

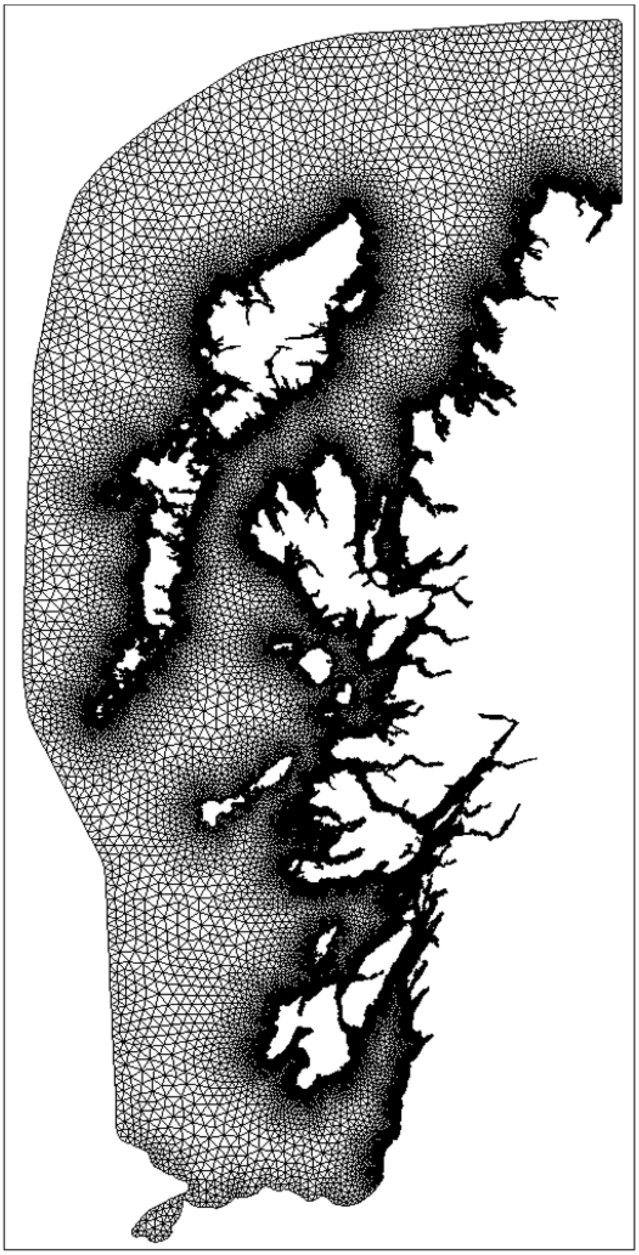

Figure 7. Mesh over entire computational domain.

Brackish water salinities at river outflows on the West Coast can be reduced by a factor of up to 1.5 compared to the far field sea values [15]. The salinity was kept constant in space and time along the river outflow boundaries with values of $S = 20$ PSU set for the rivers discharging into sea lochs. The river outflow temperatures were set to follow the air temperature and an average value (film temperature) between the local air temperature and a sea temperature of 8 °C was employed. The sea temperature value of 8 °C was deduced from the TELEMAC modelling output – see section V on validation.

Atmosphere-water heat exchange was included in the model using the WAQTEL thermic module and a first-order, lumped parameter approach [16] according to:

$$k\frac{dT}{dz} = -\frac{A}{\rho C_p}(T - T_{air}) \qquad (2)$$

The coefficient A includes for phenomena such as sensible and latent heat exchange. Reference [16] expresses the coefficient A, in W/m^2 / °C, according to the water temperature T and wind velocity V measured at the point under consideration (in m/s) according to:

$$A = (4.48 + 0.049T) + 2021.5b(1 + V)(1.12 + 0.018T + 0.00158T^2) \qquad (3)$$

The parameter b varies depending on location and a value of 0.0017 was found appropriate for this study. For turbulence closure the 2-equation *k-epsilon* turbulence model [17] was employed for both vertical and horizontal resolution.

V. MODEL VALIDATION

A. *Sea level*

Validation is against observed hydrographic data in terms of data from long-term sea level gauges as described in section III B. Fig. 8 shows the tidal gauge value comparisons.

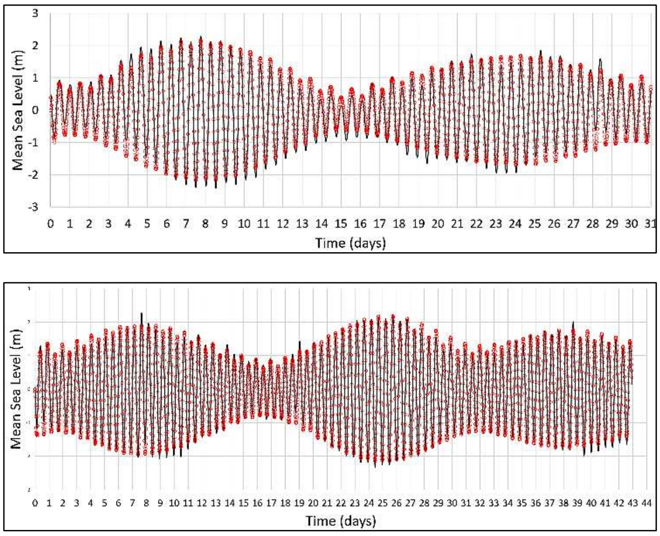

Figure 8. Sea levels at Tobermory (upper) and Loch Hourn (lower). Tobermory figures are for the period 1st – 31st October 2010. Loch Hourn is for the period 28th November 2018 – 11th January 2019. Solid black line is the BODC data and red line with symbols is the TELEMAC-3D model. All data are relative to mean sea level (MSL). Vertical axis is MSL and horizontal axis is time (days).

Fig. 8 demonstrates that the model is able to simulate the propagation of the tide across the envelope of the computational domain. Similar levels of agreement were found at Ullapool, Stornoway and Kinlochbervie (Fig. 5).

B. *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 Figs 9 and 10.

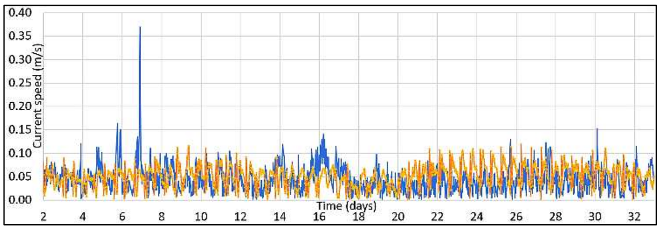

Figure 9. S Near-surface current speed magnitudes at the Loch Hourn salmon farm for the period 1st -30th December 2018. Blue lines are Mowi measured data and orange lines with symbols are the TELEMAC-3D predictions.

The average TELEMAC-3D 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.

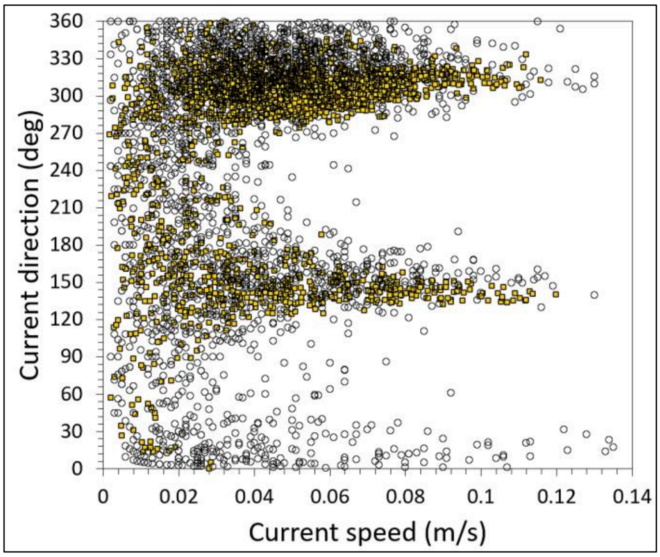

Figure 10. S Near-surface current speed magnitudes and directions for the salmon farm at Loch Hourn. Empty symbols are Mowi measured data, filled symbols are the TELEMAC-3D results.

C. *Further model validation: salinity comparisons*

The methodology for the TELEMAC-3D-WAQTEL solution is 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 and the TELEMAC-3D predictions of the salinity field are shown in Fig.11. The salinity values appear to be in reasonable agreement with the physical data.

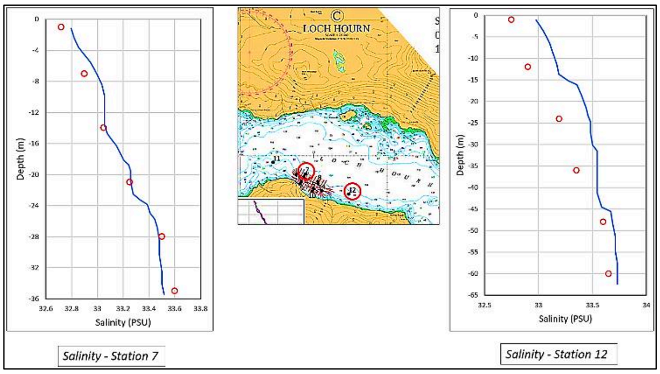

Figure 11. TELEMAC hydrodynamic model salinity versus depth at stations 7 and 12. Lines are Mowi measured data, symbols are the TELEMAC model predictions. Model data was extracted on 1st April 2019

D. *Further model validation: temperature comparisons*

Data on the temperature field in Loch Hourn were provided by Mowi and used for model validation purposes. The TELEMAC-3D hydrodynamic model sea temperature predictions at Station 7 over 89 days from 1st Feb. – 30th April 2019 are highlighted in Figure 12. This plot shows effects of atmospheric heat exchange on sea water initially at 8 ºC. The final hydrodynamic model predictions lie in the range of 7.25 to 7.5 ºC while the Mowi measured values were approximately 7.3 ºC. Although the model and measured values were taken in different years (2019 and 2021, respectively), the magnitudes appear to be in reasonable concurrence.

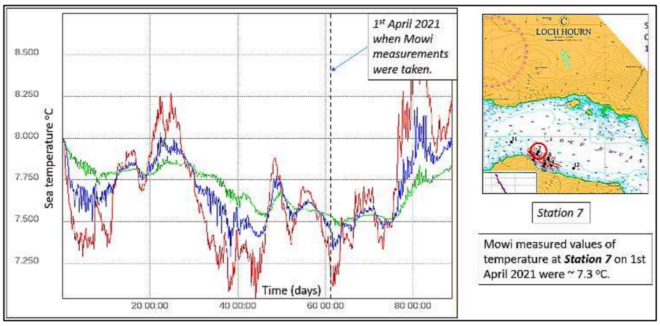

Figure 12. TELEMAC-3D-WAQTEL sea temperature predictions at Station 7 over the 89 day "spin-up" period from 1st Feb. – 30th April 2019. Plot shows influence of atmospheric heat exchange on sea water initially at 8 ºC. Colour represent different depths – red near surface, green near sea-bed.

VI. MODEL METHODOLOGY AND SAMPLE RESULTS

A. *Hydrodynamics*

As described in section V.C, the methodology for the TELEMAC-3D-WAQTEL procedure is to begin with a 3-month "*spin-up*" calculation from 1st Feb. to 30th April 2019. This allows fields of velocity, salinity and temperature to develop in the model. We then use these fields to start the particle tracking sea-lice run, using May-June 2019 data for the freshwater discharge and meteorological wind forcing.

Figures 13 to 15 demonstrate the typical flow fields predicted by the TELEMAC model at the end of the 3-month "*spin-up*" period.

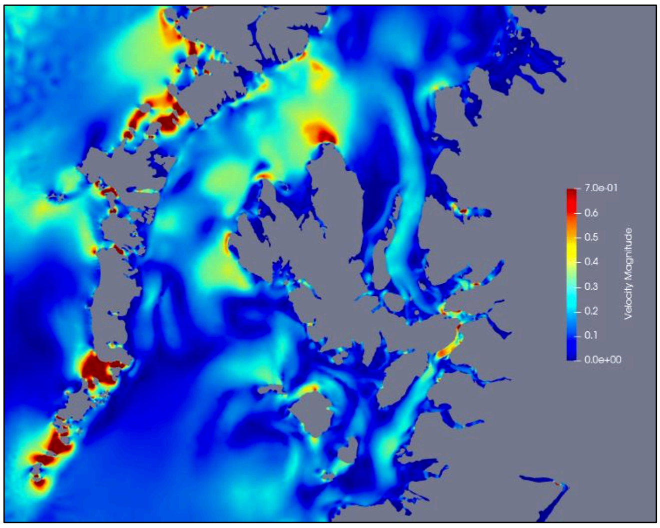

Figure 13. TELEMAC-3D-WAQTEL snapshot example of current speed magnitude (m/s) in the North-West Coast regional seas. Increased flow speeds are evident around coastal headlands, in the channels between islands and in Loch Alsh and the Kyle Rhea.

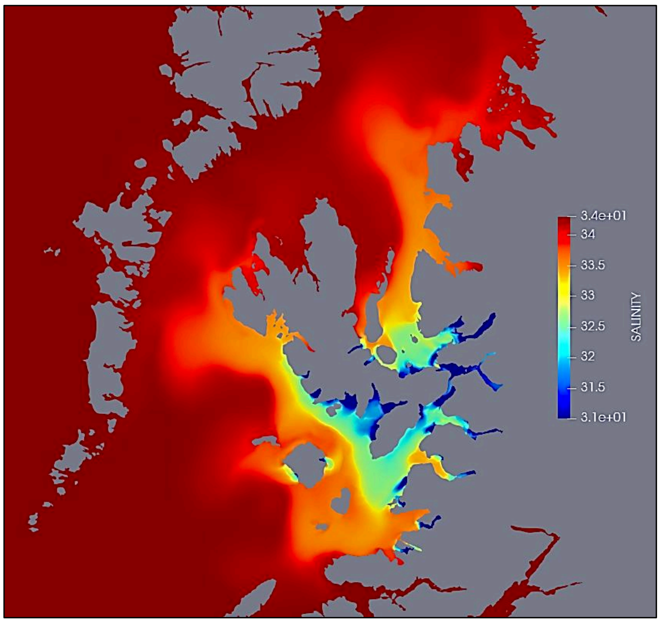

Figure 14. TELEMAC-3D-WAQTEL post- "spin-up" snapshot of near-surface salinity contours (PSU) in the North-West Coast regional seas on 1st May 2019. Freshwater discharge is ONLY from the 40 river inlet locations shown in Figure 6.

B. *Sea lice modelling*

In order to employ the open-source particle tracking code OpenDrift [4], a new reader was developed to integrate the TELEMAC Selafin file format into OpenDrift. OpenDrift was used in place of the particle tracking module in TELEMAC due to the available extra parameterization in the code. The hydrodynamic model produces flow currents for the Lagrangian transport of sea lice "particles" and an integrated biological model is employed in OpenDrift where virtual particles are released at each farm site and allowed to disperse into the marine environment. Each particle is a "super-individual", representing a number of sea lice larvae, scaled according to the salmon biomass of each farm. The biological effects of sea lice production, maturity and mortality rates and the environmental cues of salinity avoidance, temperature preference and phototactic vertical swimming behaviour (diel migration) were included [18-20].

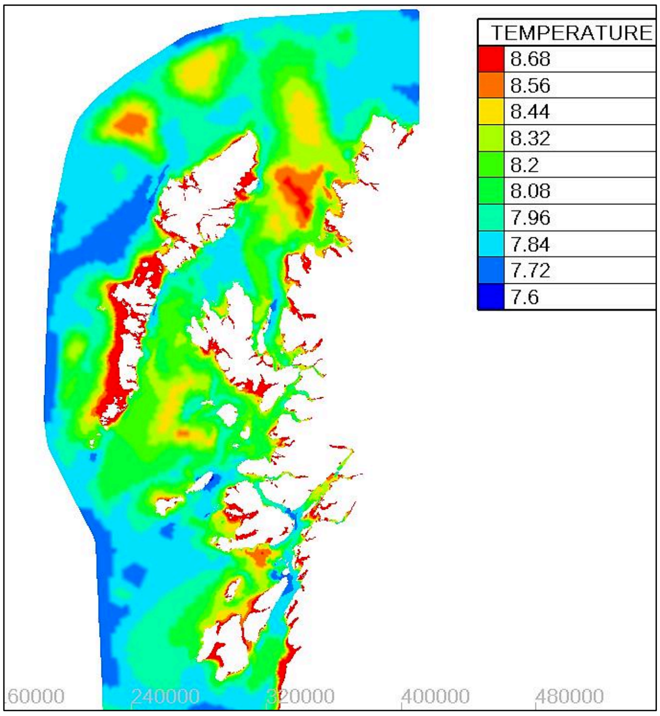

Figure 15. TELEMAC-3D-WAQTEL post- "spin-up" example of near-surface temperature (°C) contours across the North-West Coast regional seas on 1st May 2019.

Particles were introduced into the sea surface layer at the Loch Hourn farm and from 6 surrounding farms in the local area as shown in Figure 16. The period over which the sea lice dispersion model was run was 1st May – 30th June 2019.

Figure 16. The seven salmon farms involved in the sea lice study.

In Fig.17, the dispersion of particles coloured by their farm origin after 60 days is shown. The full model run can be seen as an animation at https://vimeo.com/574392901. The colours in the legend represent particles from different farms. The numbers in the legend have no significance.

This is the first stage in the sea lice modelling process and these particles do not yet represent a particular quantity of sea lice. In subsequent modelling, as each particle ages, sea lice mortality and maturity rates are applied to the population of lice that it represents. These results are then integrated at stated time and spatial intervals to calculate lice density.

Each farm releases the same fixed rate of 50 particles per farm per hour and the number of lice represented by each particle is scaled according to the farm's biomass in a particular year. The Fig. 17 results may also be viewed as indicative of how far sea lice can be transported around the West Coast before they find a fish host or die. There is potential for infective sea lice from different farms to overlap substantially as they disperse.

Results highlight the expected northwestward flow (Fig. 2) and that infective lice copepodids accumulate along tidal and salinity fronts, at the mouths of sea lochs and along shorelines, in different places according to the neap/spring tidal cycle.

Average infective copepodid densities over the period 20th May-3rd June 2019 are shown as a heat map in Fig. 18, while a snapshot of instantaneous copepodid densities is shown in Fig. 19. Both plots highlight enhanced lice densities in the areas around the mouths and southern shorelines of Loch Hourn and Loch Nevis.

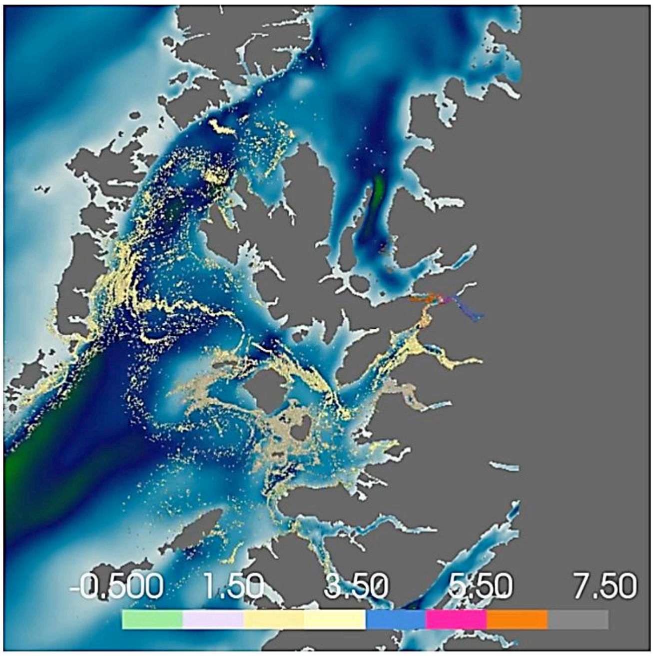

Figure 17. Sea lice distribution coloured by farm origin after **60 DAYS**. Background colour denotes bathymetry contours and the numbers in the legend have no significance. This image highlights the range of dispersion of viable infective lice copepodids but does not quantify any particular density of sea lice – see Figs.18 and 19 for sea lice densities. The full animation can be seen at *https://vimeo.com/574392901*.

VII. CONCLUSIONS AND FUTURE WORK

A hydrodynamic model of the West Coast of Scotland has been created using TELEMAC-3D-WAQTEL. The model includes the effects of complex water circulation, density and temperature gradients that persist in the West Coast seas throughout the year. These 3D phenomena appear to have been adequately captured in the model when compared with physical data. A coupled sea lice transport model has been developed which includes biological parameters for production, maturity and mortality and behavioural cues in terms of salinity, light and temperature based on published scientific literature. The TELEMAC-3D model provides a suitable data basis for modelling sea lice dispersion and an assessment of both the near-field and far-field effects. Future work will consider the risk to wild fish from sea lice originating from a greater number of salmon farms on Scotland's West Coast.

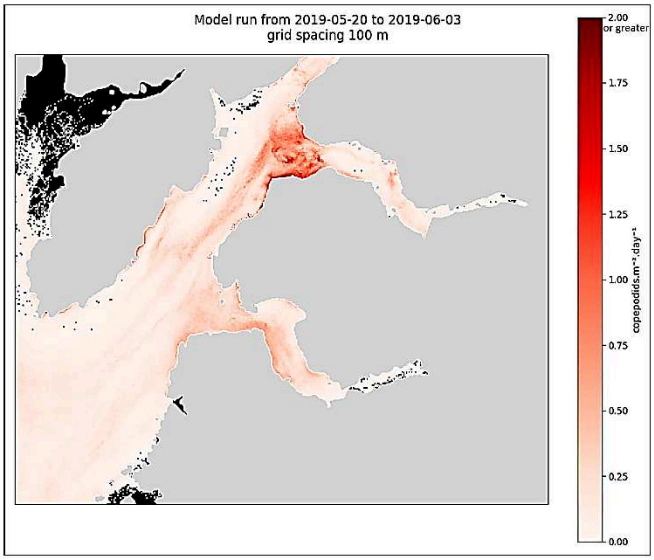

Figure 18. Heat map showing average sea lice densities (copepodids m^{-2}.day^{-1}) around Loch Hourn over 15 days of the 61-day run (20th May – 3rd June 2019). Black areas indicate zones where no lice were encountered.

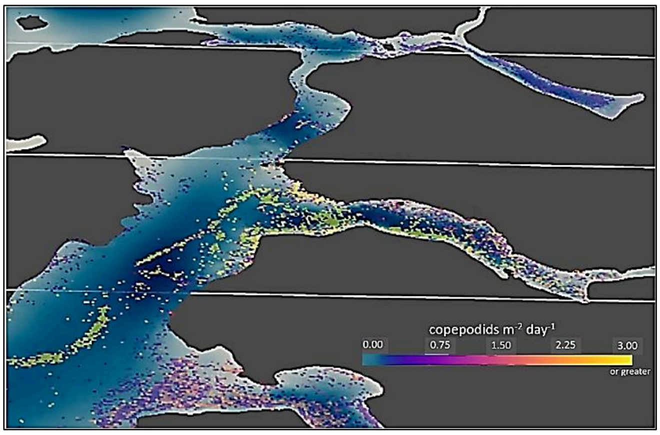

Figure 19. Snapshot of copepodid densities in the Loch Hourn region on **DAY 40** of the 61-day model run, recalculated at hourly intervals and converted to equivalent daily averages. Background colour denotes bathymetry contours. The full animations can be seen at https://vimeo.com/574396820 and https://vimeo.com/574402482.

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