Modelling of the Proposed Salmon Farm at Little Colonsay

Part 5. Salmon Lice

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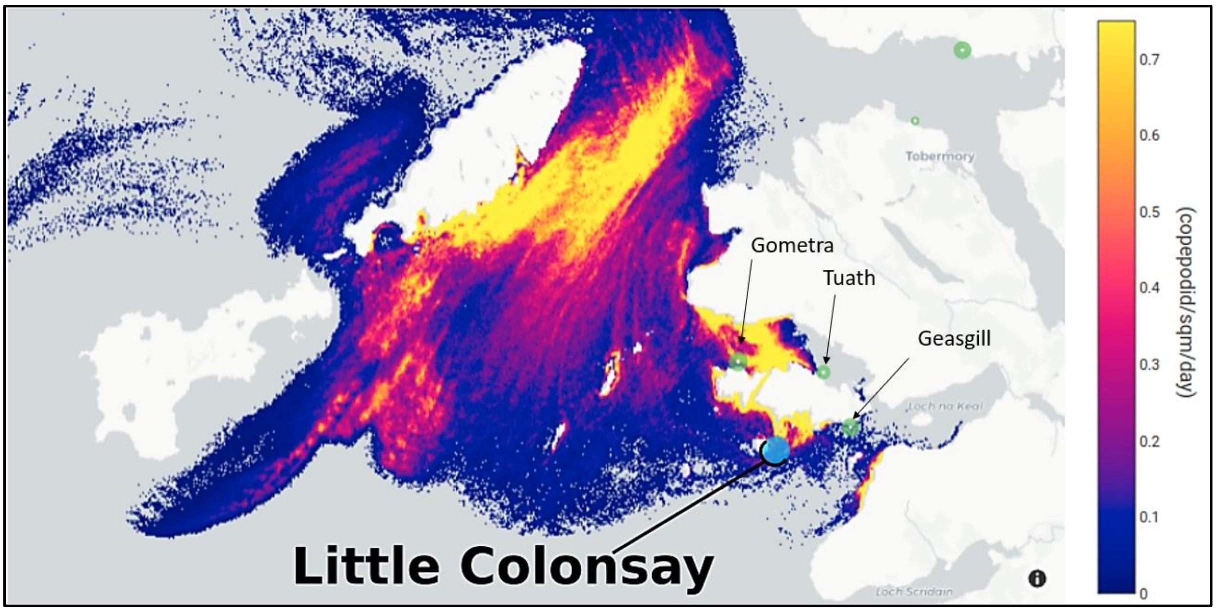

Executive Summary

A Bakkafrost salmon farm at Little Colonsay has been proposed with a future maximum biomass of 2773 tonnes.

Farmed salmon are hosts for parasitic salmon lice (*Lepeophtheirus salmonis)* which are proven to harm wild salmon and sea trout [Johnsen_2020; Sandvik_2020, ScotGov_2021]. In order to assess the risk that wild salmon and sea trout will be harmed by the proposed Little Colonsay farm, Simon Cowell has commissioned the development of a detailed hydrodynamic and biological model of the area. The model simulates water levels and flows (i.e., currents and tides), which govern the transport of organic material and salmon lice emanating from the fish farms. The proposed farm and all other surrounding farms are included in the model for biomass conditions in the years 2017, 2018 and 2019.

In an integrated biological model, virtual particles were released at each farm site and allowed to disperse into the marine environment. Each particle is a "super-individual", representing a number of salmon lice larvae. The biological effects of salmon lice production, maturity and mortality rates, salinity avoidance, temperature preference and phototactic vertical swimming behaviour (diel migration) were included. The outputs from the modelling can also be used to determine other risks from these projects, including operational risks and pollution risks.

A three-dimensional hydrodynamic (HD) model of the West Coast of Scotland was constructed using the Telemac3D code [Scanlon_A, 2023], [Scanlon_B, 2023]. The model domain extends from the Mull of Kintyre in the South to Whitten Head in the North and includes all main islands off the West Coast. The computational mesh was constructed using a flexible mesh approach with a varying spatial resolution down to tens of metres at river inlets.

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 Little Colonsay 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 on the modelled current speeds was included for the time of year of the study [ERA_2023]. Coriolis force for Earth spin was also included in the model.

The hydrodynamic model was validated against published observed hydrographic data (water levels and currents) from around the West Coast [Scanlon_A_2023], [Scanlon_B_2023] and in the Little Colonsay area itself [MTS_CFD_hydro_LC_2023]. 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 operator Bakkafrost.

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 around the West Coast 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 Little Colonsay.

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 salmon lice impact on wild salmon and sea trout and an assessment of both the near-field and far-field (regional/dispersion) effects compensating for the absence of direct field measurements.

The use of hydrodynamic modelling to predict salmon lice densities and the risk presented to wild salmonids is increasingly common, particularly in Norway [Johnsen_2020], [Asplin_2020]. Marine Scotland and SEPA are working on similar projects in Scotland. The integrated biological model draws on the methods and assumptions used by Scottish and Norwegian modellers working for government agencies, as well as other peer-reviewed research.

The modelling outputs show how lice densities change spatially and over time. To best assist decision-makers' assessments of the long-term risks to salmon populations, this data needs to be presented in such a way that the most significant risk is apparent.

The risk of infestation by salmon lice varies according to the density of lice to which the fish are exposed and the duration of that exposure [Johnsen_2020], [ScotGov_2021]. 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 salmon lice densities averaged over two months do not best represent the risk they face. In this report the model outputs are presented in two ways, to demonstrate how the salmon lice density and therefore the apparent risk vary:

1. Infective lice (copepodid) densities averaged over a 26-day period in May 2017, 2018 and 2019, shown as a heat map.
2. Copepodid densities calculated every hour, and converted to equivalent daily lice density, shown as an animated series of lice density maps. 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 underlying hydrodynamic and biological modelling assumptions are identical.

The animations and heat maps show that infective 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. Densities in these areas can be very much higher than the long-term, large-scale average. These lice aggregations are displaced locally by the flow of water but the high densities are conserved for many days.

Migrating fish may be at significant risk of infestation when exposed to such high copepodid densities, even for short periods [Johnsen_2020], [Sandvik_2020], [ScotGov_2021].

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 Julien Moreau *MSc, MSc, PhD, Basin Analyst, geology and applied geophysics consultant at the* NW-Edge, *Strategic development and research leader at* Plastic@Bay.

Julien is a geoscientist with over 20 years of experience. After a first degree in biology at the University of Lyon (France, 1998), Julien acquired a MSc in sedimentology at the University of Lille (France, 2001) with the Mining School of Paris. He then took a PhD in Sedimentology at Strasbourg University (France, 2005). Julien got a doctoral grant to diversify and include numerical modelling and exploration geophysics during his PhD and a year postdoc in Strasbourg. In 2007, he was hired for 3 years at the University of Aberdeen to work on regional scale geophysics, looking at the last glaciations in the North Sea. After a short stay at the University of Manchester, he worked one year for the Mining school of Paris, developing inversion methods guiding a numerical code simulating meandering rivers (FLUMY). In 2010, Julien then joined the geophysics department of the University of Helsinki (NATO) to work on crustal imaging with reflection seismic and georadar exploration for environmental assessment of mining sites. In 2012, he obtained a 4-year assistant professor position at the University of Copenhagen to work on the multiscale geophysical evaluation of chalk. During that time, he acquired a MSc in teaching for higher education. In 2016, Julien moved to the NW of Scotland and started working on the problem of marine plastic, founding Plastic@Bay to integrate research, community work and circular economy to tackle marine pollution. Julien has contributed to numerous peer-reviewed papers, short communications, reports and a few educational books. He continues to do geoscientific and environmental consultancy through his company the NW-Edge. Most of his current research efforts are now directed towards low-tech recycling of ocean plastics and oceanographic-environmental modelling.

1 Introduction

1.1 *Background to the study*

This report has been prepared for Simon Cowell by engineering consultants MTS-CFD and The NW-Edge, as part of hydrodynamic modelling services to consider the impact of salmon lice from the proposed Bakkafrost fish farm site at Little Colonsay, as shown in Figure 1.1.

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.

This report describes the construction of a hydrodynamic model of the West Coast of Scotland with a focus on Little Colonsay, simulating water levels and flows (i.e., currents and tides) and its use to model the transport of salmon lice originating from fish farms.

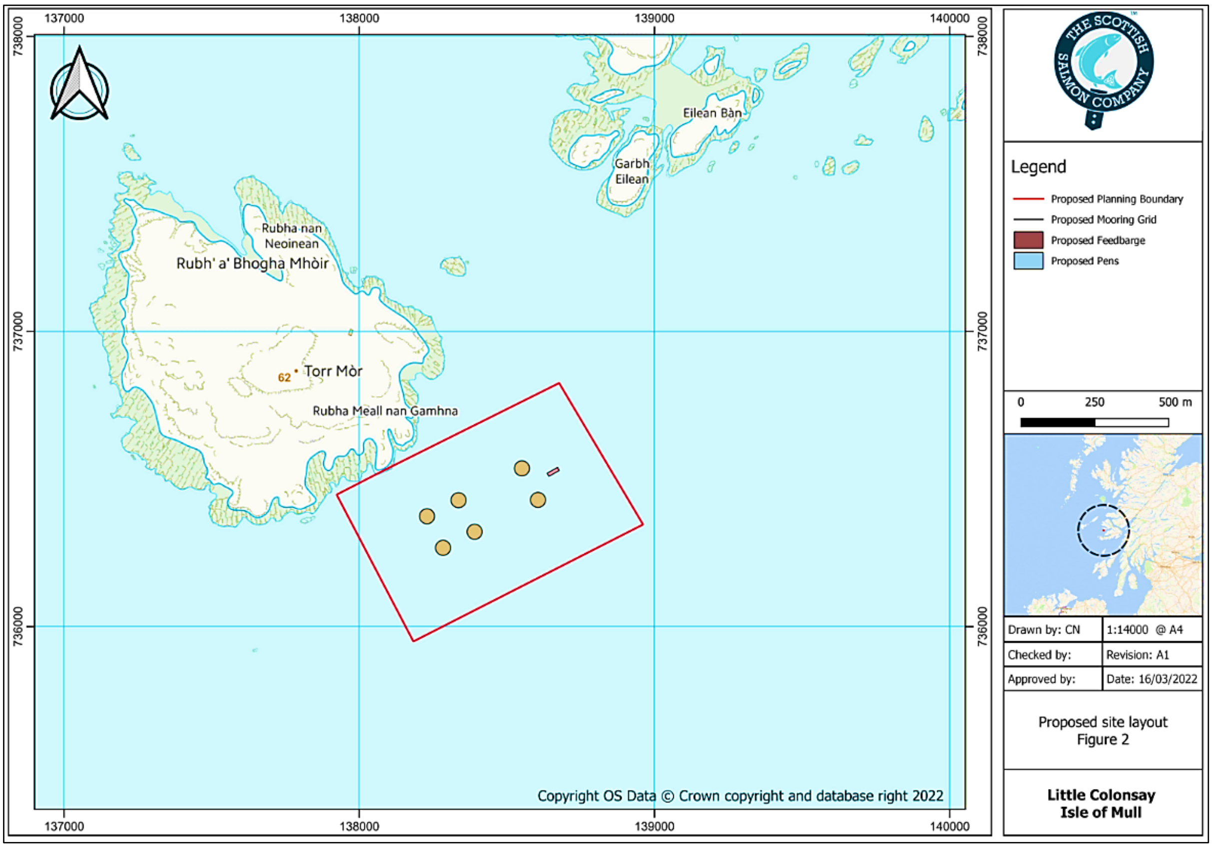

Figure 1.1 *Geographic location of the proposed Bakkafrost salmon farm at Little Colonsay (inset on lower right shows the general location).*

1.2 *Project objectives*

The objectives of the study are:

1. To construct a 3D HD model of the West Coast and Little Colonsay, describing the spatial-temporal flow environment (water levels and current speeds).

2. To implement a biological salmon-lice model.
3. To test the sensitivity of the models to various input settings and validate the model predictions using physical measurements; and
4. To run the validated HD and salmon lice model for a period of 26 days, during which time salmon lice copepodid numbers will stabilise, allowing their changing density distribution to be mapped.

1.3 *Layout of this report*

The remaining sections of this report are organised as follows:

- Section 2 provides further information on the geographic and hydrodynamic setting of the study area;
- Section 3 outlines the available data used as the basis for the modelling study, including information on bathymetry, water levels, currents, and meteorological conditions;
- Section 4 describes the development of the 3D HD model of the West Coast and the results from model sensitivity tests;
- Section 5 provides some hydrodynamics results and describes the salmon lice model;
- Section 6 discusses the results of the HD model validation and salmon lice model results;
- Section 7 draws some conclusions from the HD-salmon lice model development at Little Colonsay and the surrounding area.

2 Geographic and hydrodynamic setting

2.1 *General topography and flow features*

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 fresh water discharging from the land [Offshore_Energy_SEA_2021]. Overall circulation patterns (Figure 2.1) 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 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 2.2 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 Telemac3D hydrodynamic model for the West Coast and at Little Colonsay is provided elsewhere [Scanlon_A, 2023], [Scanlon_B, 2023], [MTS_CFD_hydro_LC, 2023] and is only summarised in this report.

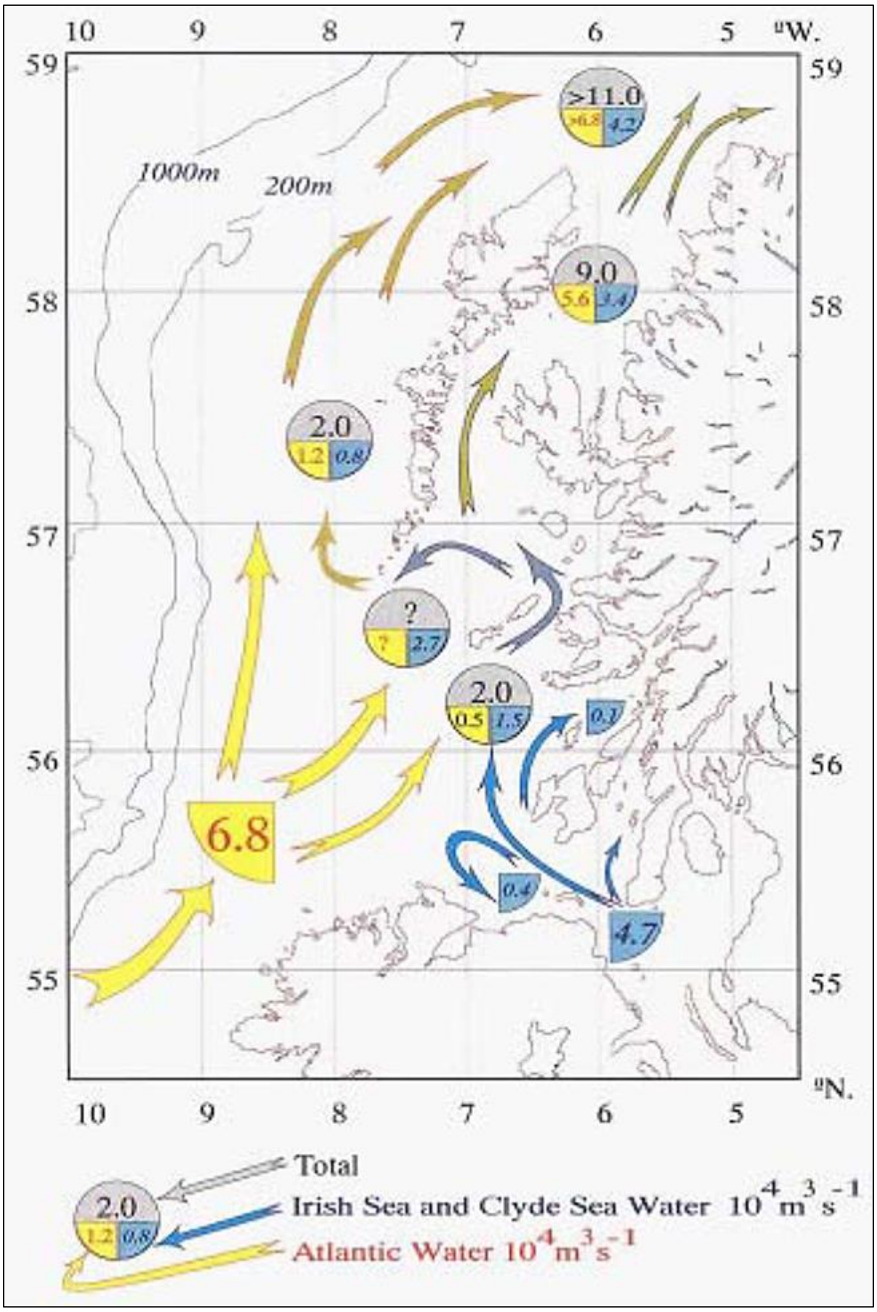

Figure 2.1 *West Coast of Scotland general circulation patterns and approximate volume fluxes* (*Offshore Energy SEA, 2021*).

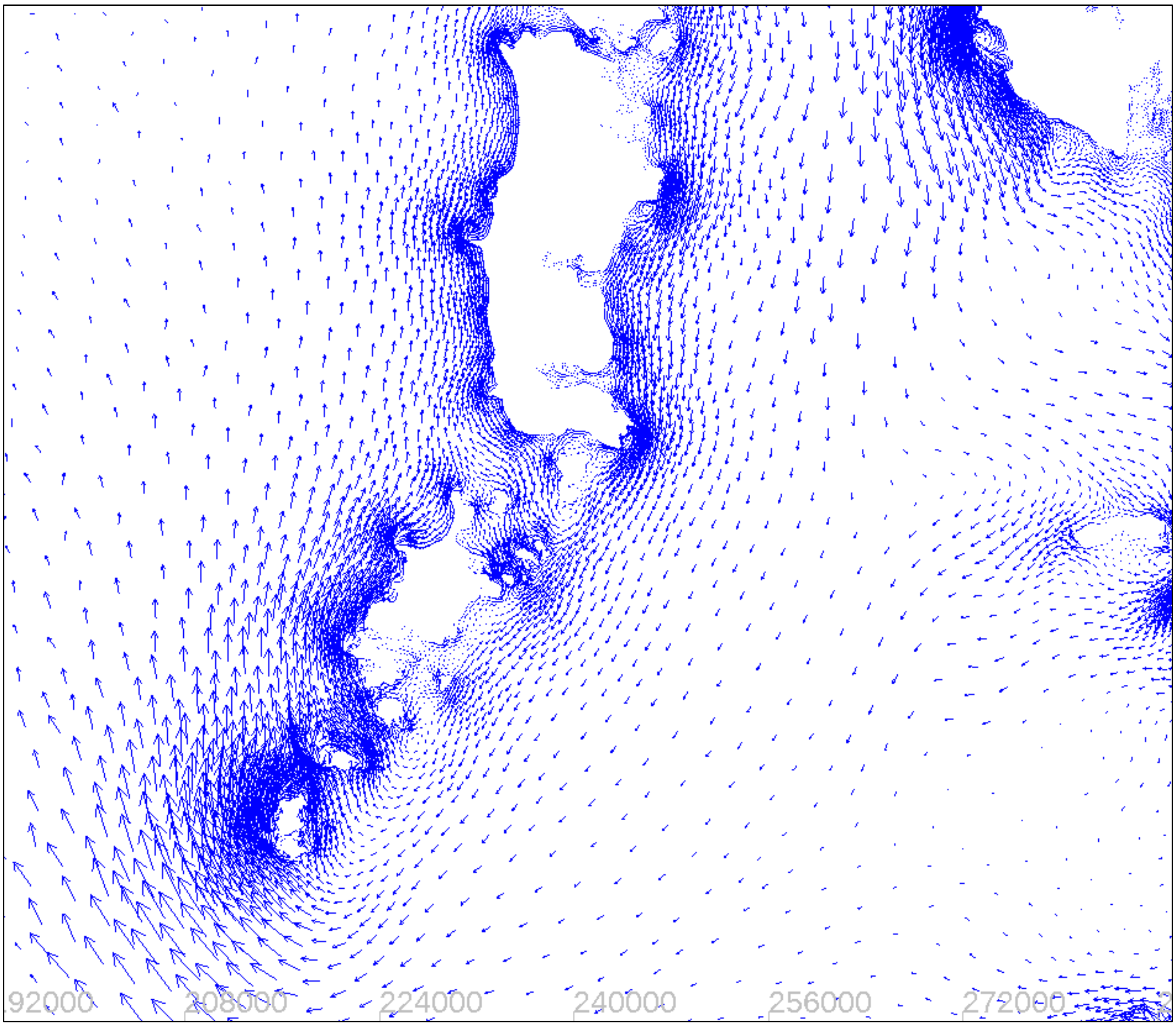

Figure 2.2 *Example of clockwise circulation around South Uist, Barra and Mingulay produced using the Telemac 3D hydrodynamic model.*

3 Available Data

This section summarises the data used during the modelling process.

3.1 *Bathymetry data*

The bathymetry data for the present study have been collected from a range of different sources including publicly available datasets provided by Marine Scotland for the Scottish Shelf Model [SSM_2023], digitised Admiralty charts and bathymetry information from the UK's Digimap Ordnance Survey Collection [DOSC_2023]. The bathymetry and spatial extent of the model is shown in Figure 3.1.

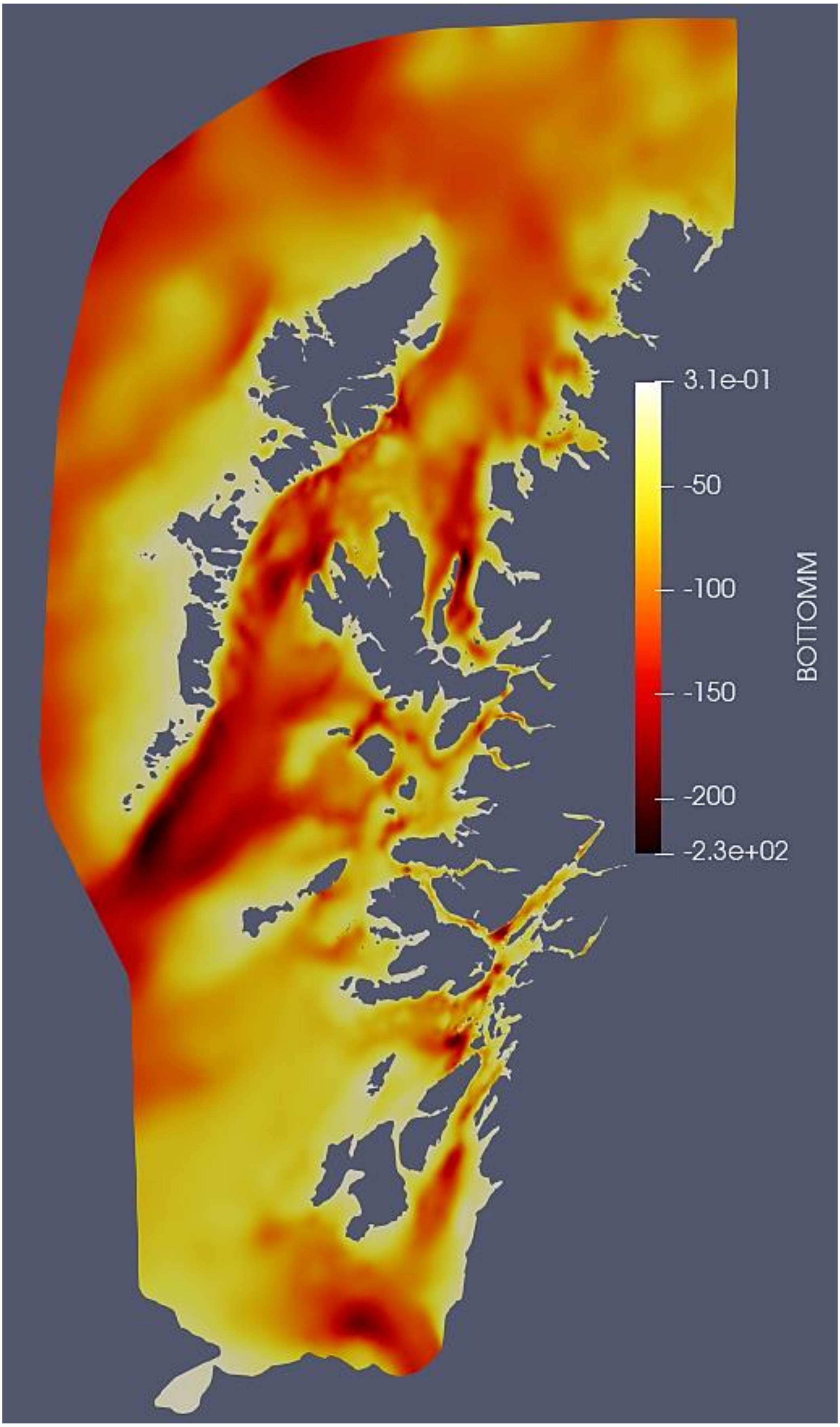

Figure 3.1 *Model bathymetry (m) and spatial extent of model*

3.4 *Meteorological data*

Meteorological data consist of information on wind speed and direction. Wind forcing is included in the hydrodynamics model based on weather data at 6-hourly intervals [ERA, 2023].

3.5 *Freshwater sources*

Data for freshwater sources (i.e., river run off) entering the inner seas around Little Colonsay and the surrounding area 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]. There were a total of 168 rivers implemented in the model.

3.6 Fish pathways

Recently, the Atlantic Salmon Trust has released preliminary smolt tracking data from 2021 and 2022 (https://atlanticsalmontrust.org/our-work/the-west-coast-tracking-project/). The data show salmon actively swimming around the Isle of Mull from both the Sound of Mull to the East and the Passage of Tiree to the West (Fig. 3.2). From the river Orchy to the entrance of the Sound of Mull it took 4 days for a fish to swim. From the same river to the southern part of the Outer Hebrides, it took 16 days. These timing are critical when calculating the exposure time of fish to pollution/infestation.

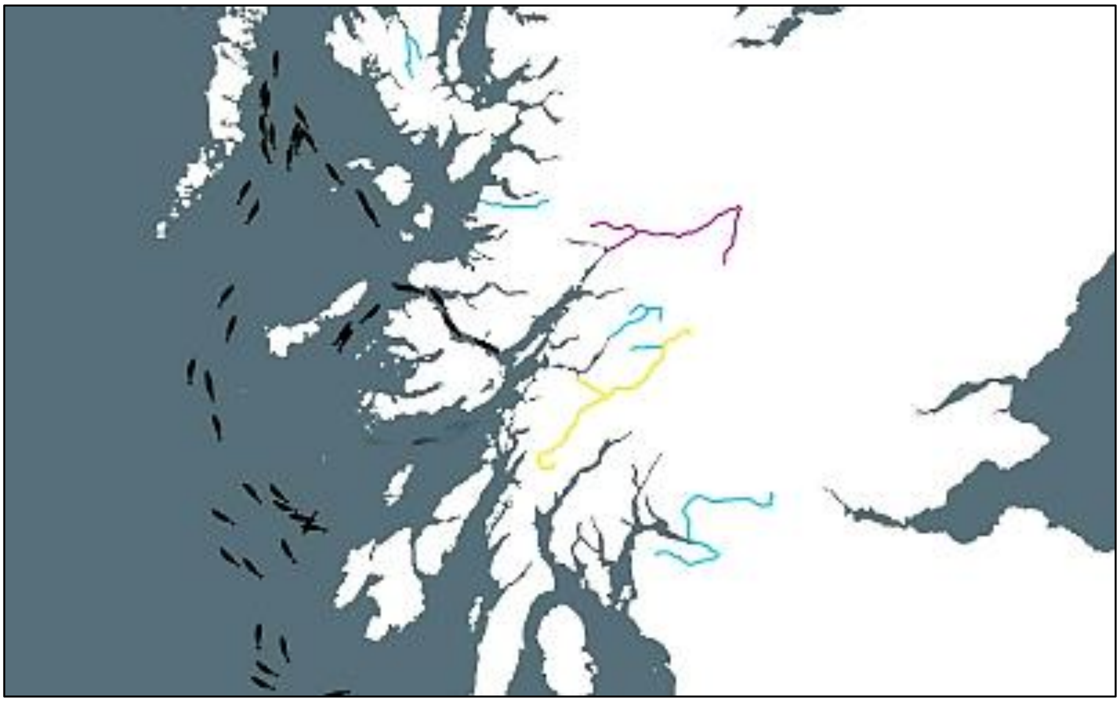

Figure 3.2 *Screenshot from the Atlantic Salmon Trust second video at 3 min (https://atlanticsalmontrust.org/our-work/the-west-coast-tracking-project/). The illustration shows smolts swimming around the Isle of Mull.*

4 Model Development

4.1 *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_2023] and is also listed as a hydrodynamic technology by the Crown Estate [UK_Crown_Estate_2023].

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;
- Particle tracking for salmon lice;
- Biological salmon lice model;

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

4.2 *Domain, mesh and bathymetry*

4.2.1 *Model domain*

The domain of the Telemac model developed for Little Colonsay study was shown in Figure 3.1. 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 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).

4.2.2 *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_2023] 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.

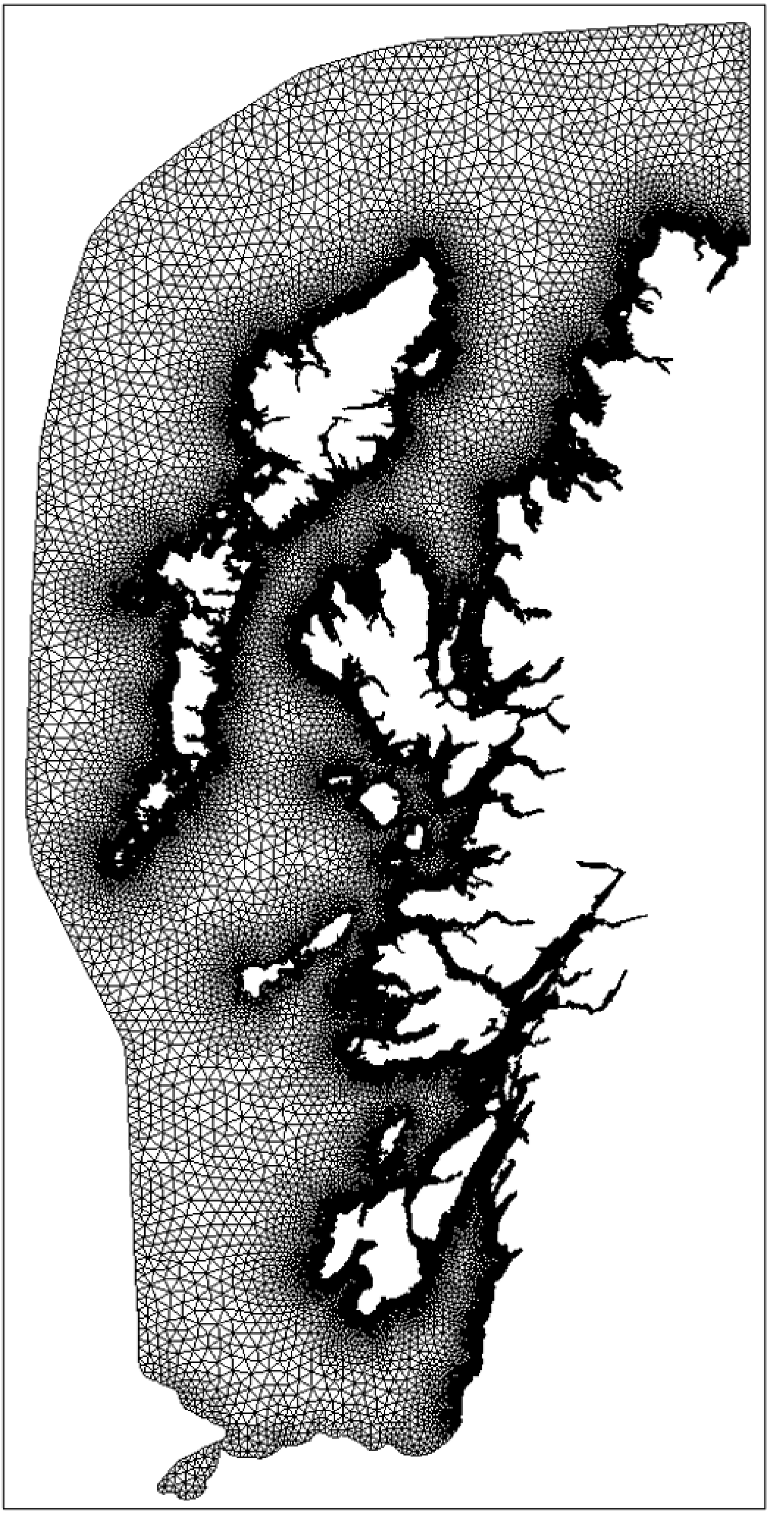

Figure 4.1 *Telemac mesh over the entire computational domain.*

Figures 4.2 to 4.4 show the computational mesh in the upper, middle and lower regions and Figure 4.5 shows the mesh resolution around the inner seas at Little Colonsay.

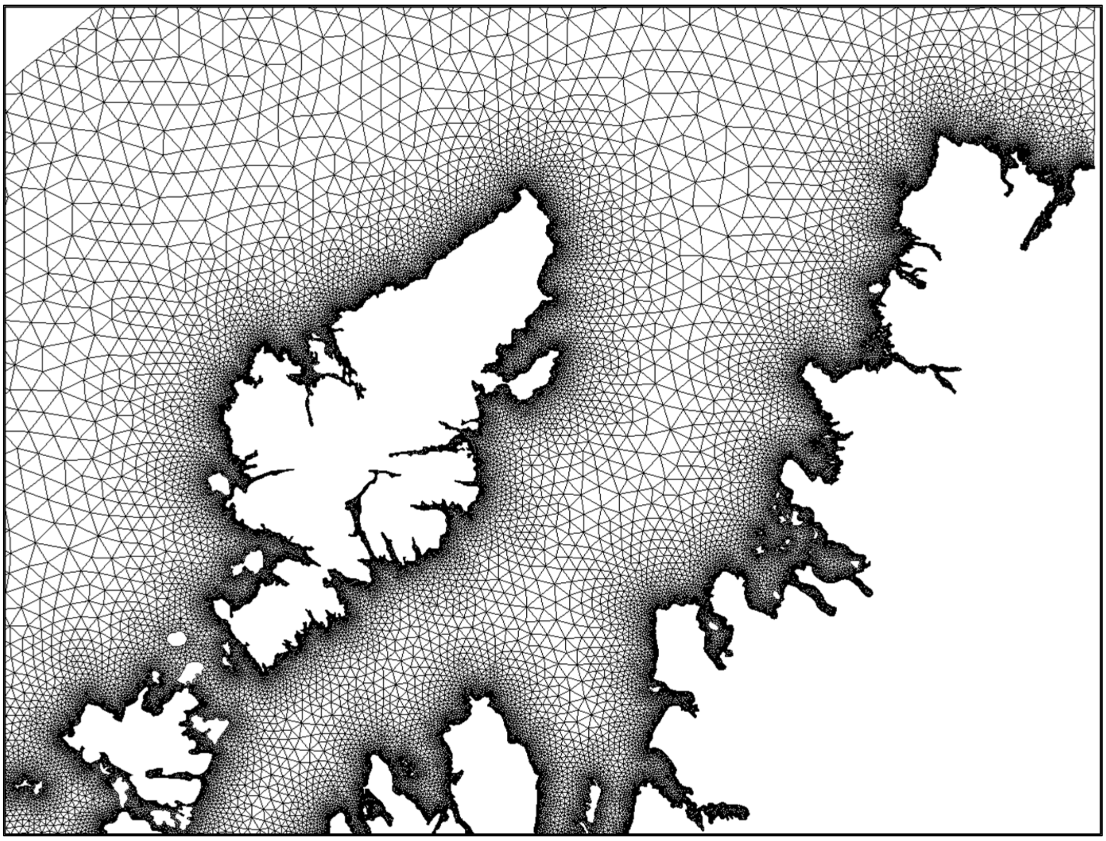

Figure 4.2 *Telemac mesh over the Northern section.*

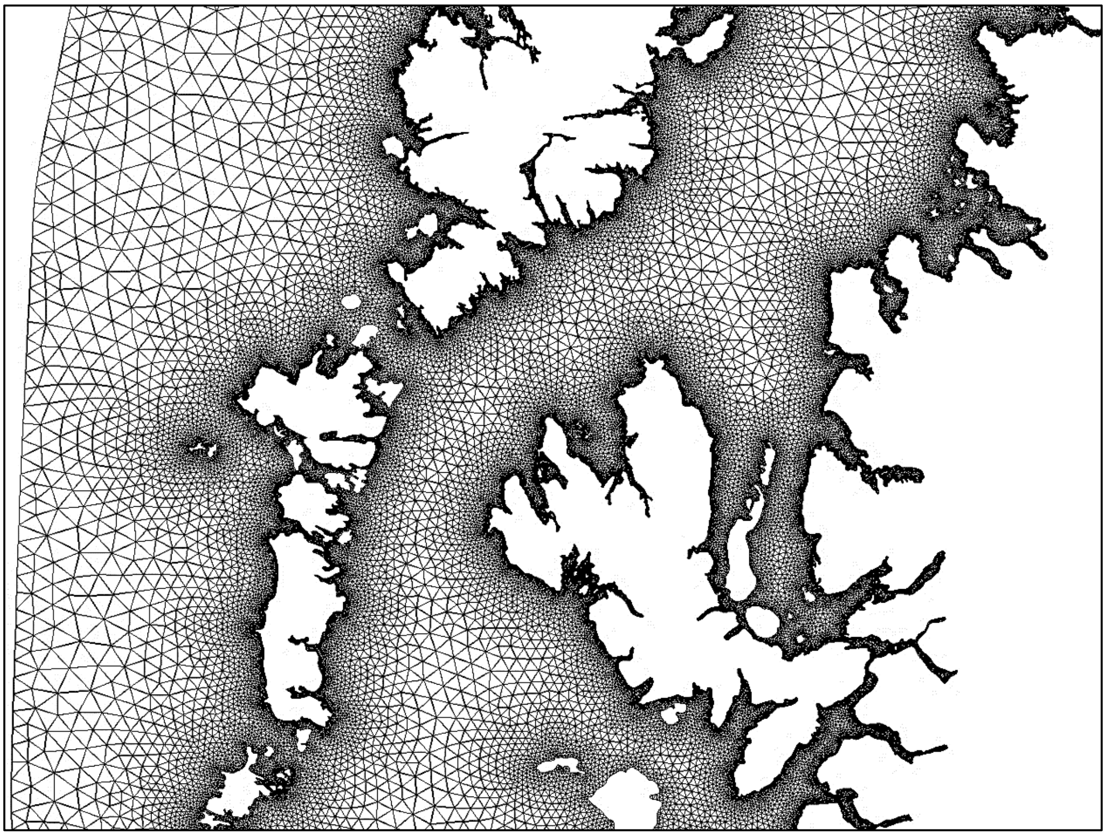

Figure 4.3 *Telemac mesh over the middle section.*

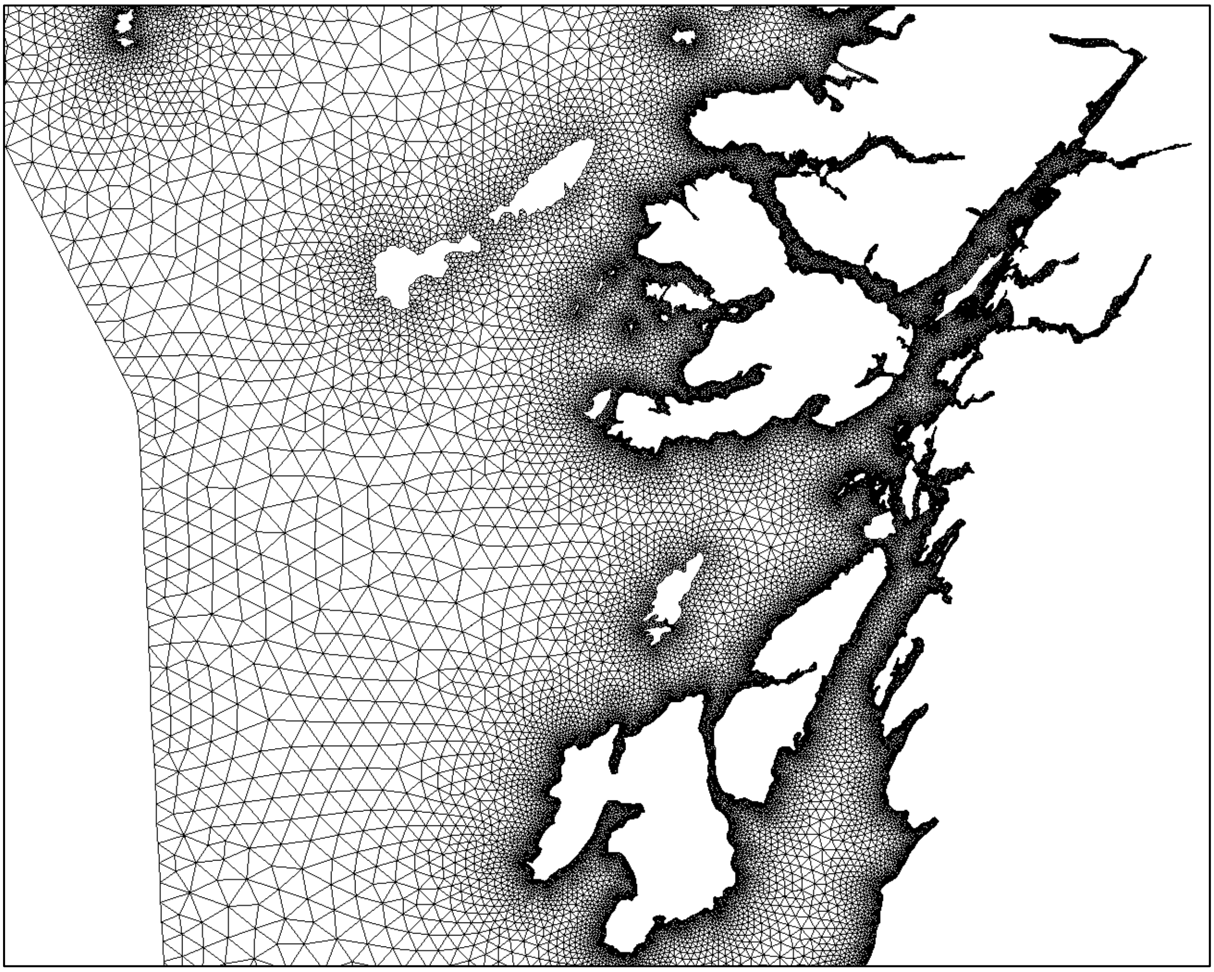

Figure 4.4 *Telemac mesh over the Southern section.*

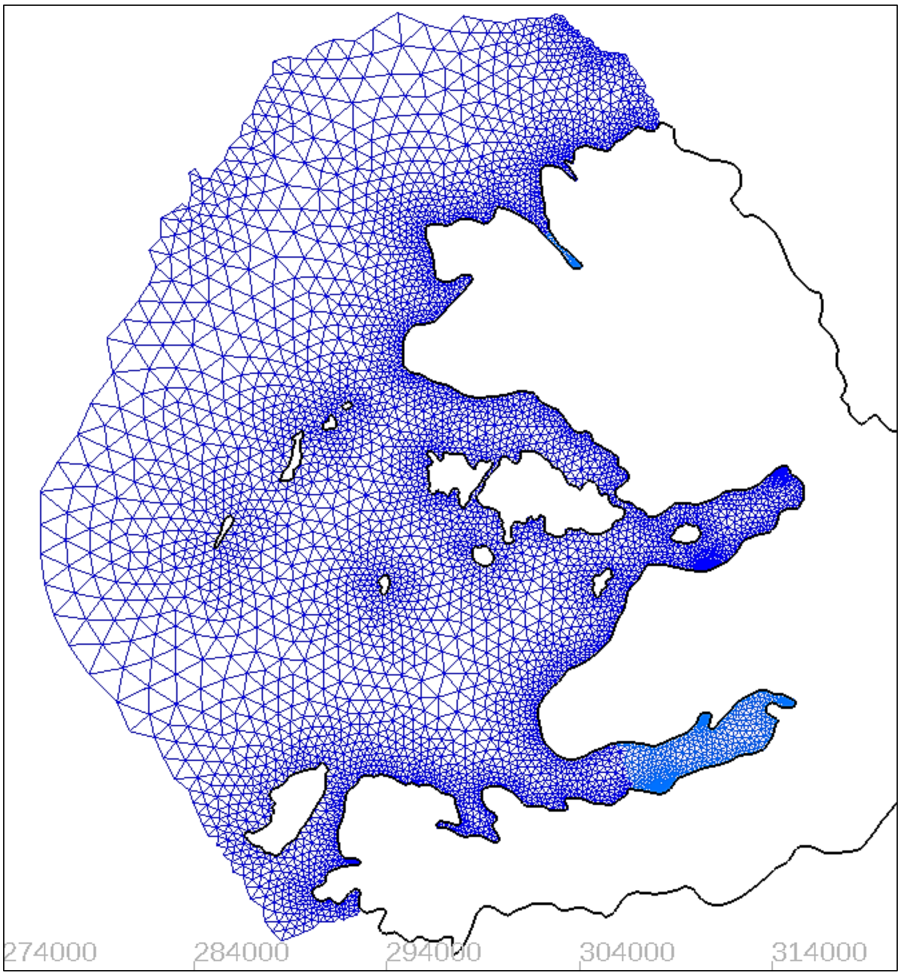

Figure 4.5 *Sample of Telemac mesh in the Little Colonsay area.*

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

4.3 *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_2002]. Initial values of temperature and salinity were set to 9 ^{o}C and 34.3 PSU, respectively, and zero-gradient boundary conditions applied at the open sea boundaries.

4.4 *Meteorological forcing*

Winds can play an important role in the hydrography of the West Coast and the meteorological forcing data was taken from [ERA_2023] as described in section 3.4.

4.5 *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. 10 vertical mesh layers were selected to follow the meshing strategy of [Sabatino_2016]. Ultimately, there is a balance to be struck between levels of detail and computational run times.

4.6 *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 the inner seas around Little Colonsay 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* (ºC) and salinity *S* (PSU):

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

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 [Marine_Scotland_2012]. The salinity was kept constant in space and time along the river outflow boundaries with values ranging between S = 0 and *S* = 20 PSU set for the rivers discharging into sea lochs. Following the work of [Sabatino_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 initial sea temperature of 9 ºC 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 / ºC, 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 0.0017 was found appropriate for this study [Scanlon_A, 2023].

For turbulence closure the 2-equation *k-epsilon* turbulence model [Launder_1974] was employed for both vertical and horizontal resolution.

5 Model Methodology and Sample Results

5.1 *Hydrodynamics*

The methodology for the Telemac procedure is to begin with a 1-month "spin-up" calculation from 1st April to 30th April 2018. 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 2018 data for the freshwater discharge and meteorological wind forcing.

Figures 5.1 and 5.2 show snapshots of the typical flow fields predicted by the Telemac model in May 2018. Figure 5.3 shows a snapshot of the surface salinity field in May 2018.

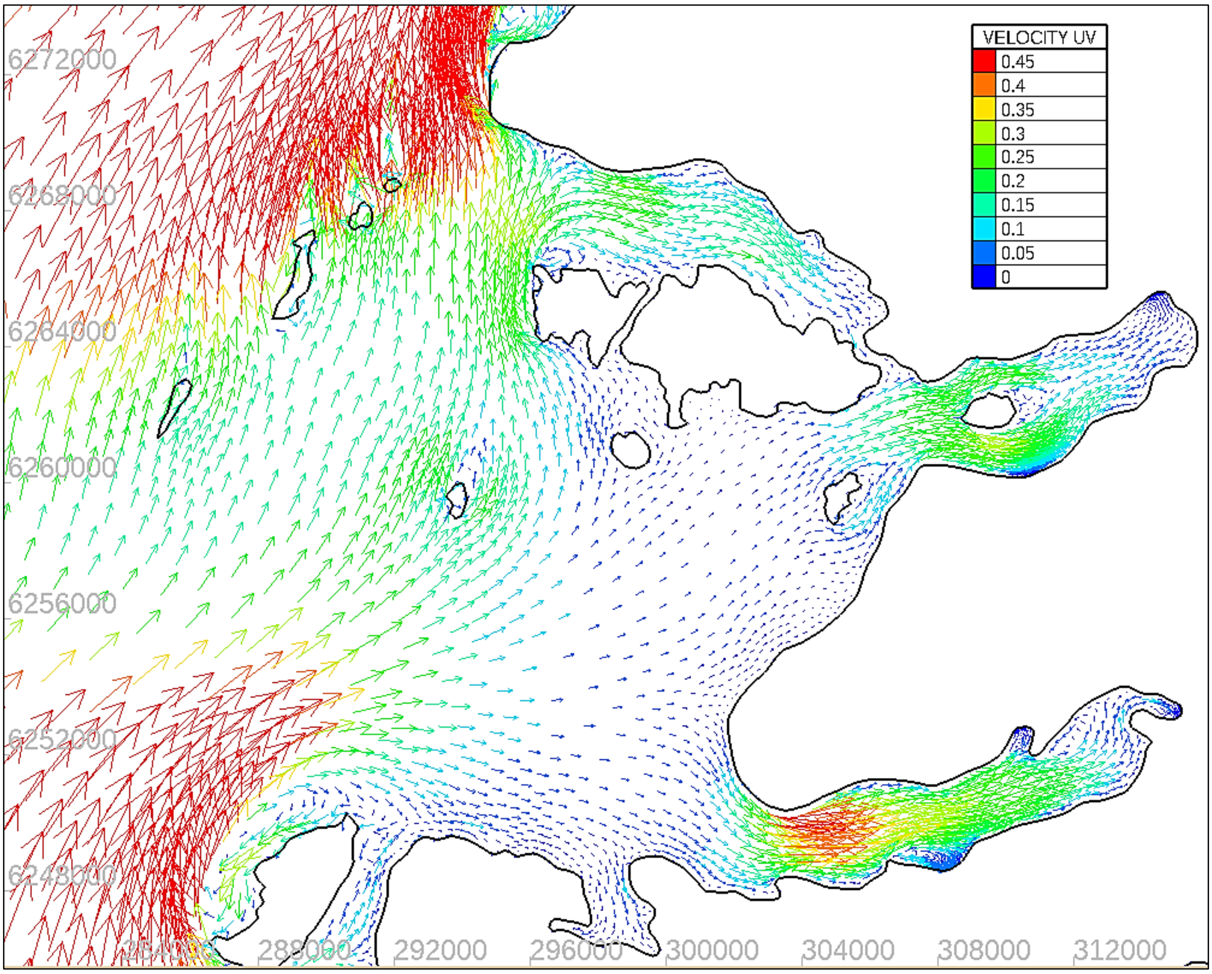

Figure 5.1 *Snapshot example of current velocity (m/s) during a flood tide in May 2018.*

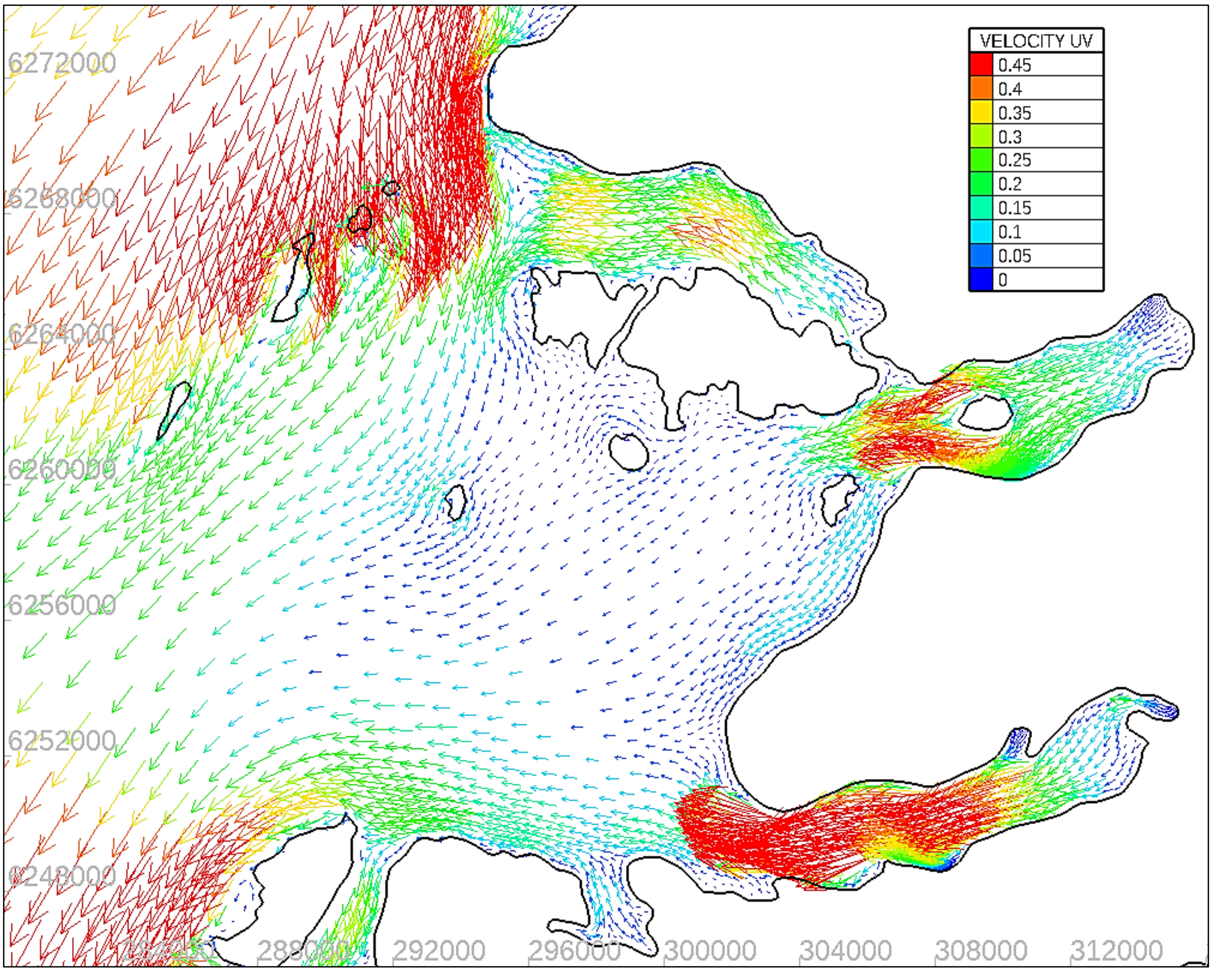

Figure 5.2 *Snapshot example of current velocity (m/s) during an ebb tide in May 2018.*

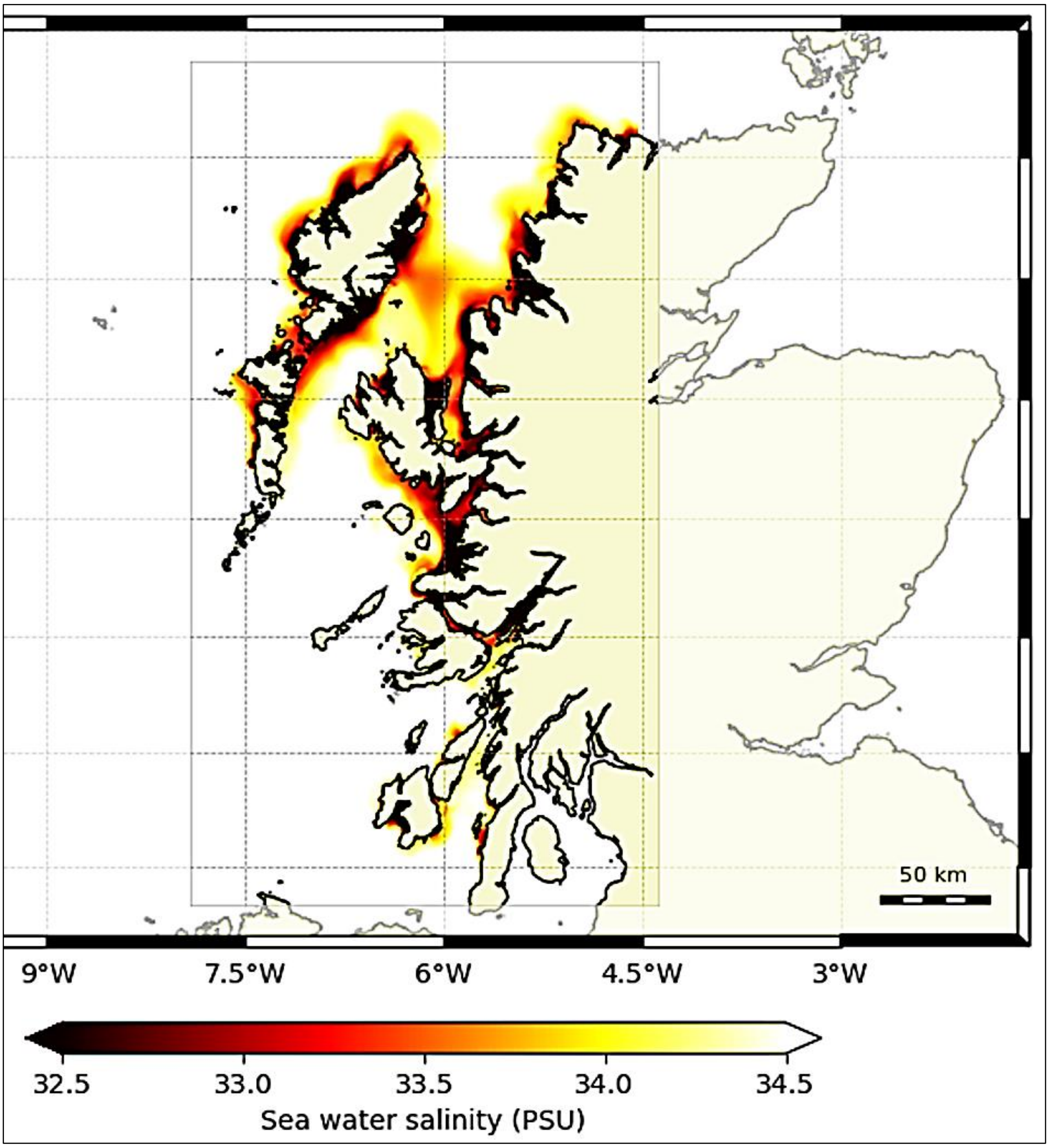

Figure 5.3 *Snapshot of surface salinity (PSU) across the West Coast in May 2018.*

5.2 *Salmon lice modelling*

5.2.1 *Salmon farm location and biomass*

The hydrodynamic model produces flow currents for the Lagrangian transport of salmon lice "particles". Each particle may be thought of as representing a "packet" or "super-individual" of salmon lice. Particles were introduced into the sea surface layer at the Little Colonsay farm and from all surrounding farms in the vicinity and across the West Coast of Scotland. The biomass of the Little Colonsay farm was taken as 2773 tonnes and 3 different years of production were considered; 2017, 2018 and 2019. The biomasses of the surrounding farms for each year may be found at https://192-171-169-124.sslip.io/ and figure 5.4.

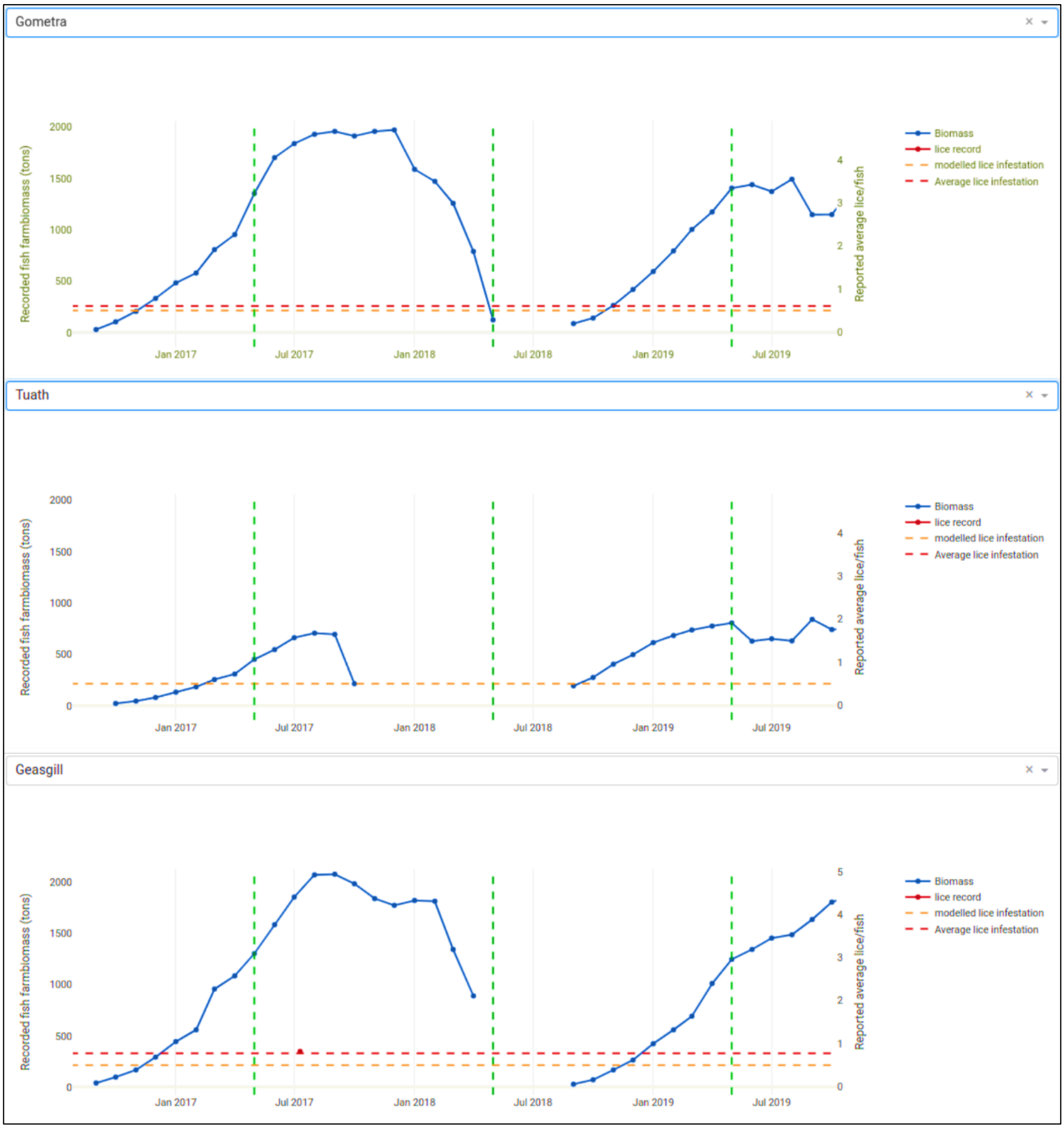

Figure 5.4 *Biomass production cycles (blue line) 2017-2019 for the 3 active farms close to Little Colonsay – Gometra, Tuath and Geasgill.*

5.2.2 *Salmon lice model description*

The particles in the sea-lice model were subject to the environmental cues of salinity, light and temperature and the following biological and physical features:

1. The source of nauplii was using the value of 30 nauplii released per adult female louse per hour [Stein_2005]. This empirical value was the one recommended by Marine Scotland and MOWI expert modellers [Murray_Gillibrand_pers_comm_2022].

2. For all farms the average fish weight was estimated to be 4.5 kg.

3. The particle release rate was 50 super particles per farm per hour.

4. Lice densities were calculated on meshes of varying cell size with the highest resolution being 50 m × 50 m.

5. The development of nauplii into infective copepodids is temperature-dependent. The model uses 40 degree-days for the first moulting stage into copepodids (Sandvik *et al*., 2020). As the particles mainly encounter an 11 ^{o}C temperature in May 2018, the first copepodids appear around 3.63 days after the hatch. The nauplii of the super-individual particles will mature into copepodids at a rate of 10% per hour from 3.63 days. This maturity parameter has also been employed in the published work of Marine Scotland and SAMS [Salama_2013], [Salama_2016], [Salama_2018], [Adams_2012], [Adams_2016].

6. The planktonic sea-lice are considered to be slightly heavier than the surrounding sea water. To match their natural living space, the maximum achievable depth is set to 50 m, [Johnsen_2014]. The maximum speed upward or downward was estimated as 0.75 mm.s^{-1} to match the absolute speeds used in [Sandvik_2020] of 0.5 and 1 mm.s^{-1} upward and downward, respectively. In case the lice are exposed to salinities lower than 27 PSU, they would not be capable of actively swimming and are given a sinking speed of 0.25 mm.s^{-1}. In the unlikely absence of stimulus (light, salinity or temperature) the lice would also be sinking naturally.

7. Both the nauplii and copepodid stages were given phototactic vertical swimming behaviour (upward swimming when light levels exceeded a critical value of irradiance relevant to the biological stage) [Johnsen_2016], [Myksvoll_2018], [Sandvik_2020]. In the absence of an overlaying low-salinity layer, planktonic salmon lice will swim upwards when the light levels exceed 2.105×10^{-5} and 0.395 µmol photons.s^{-1}.m^{-2} for nauplii and copepodids, respectively [Sandvik_2020].

8. Lice prioritise avoiding low salinity water (< 32 PSU) over swimming towards the light, by downward swimming [Bricknell_2006], [Myksvoll_2018]. If lice encounter salinities under 27 PSU, they lose their ability to swim and simply sink [Novales_Flamarique_2000], [Sandvik_2020].

9. The copepodid stage can also react to the environmental cue of temperature. Particles in the model are capable of sensing temperature just above or below their vertical positions. They may choose to swim up or down towards warmer waters if they are not simultaneously affected by salinity or light triggers [Samsing_2016].

10. The chosen mortality rate for nauplii and copepodids is 0.17 d^{-1} [Johnsen_2014].

11. A Fourth-order Runge-Kutta solver of the ballistic equation of motion includes the effects of stochastic turbulent diffusion [Salama_2013] and particles are subject to a horizontal eddy diffusion of 0.1 m^{2}.s^{-1} and a vertical eddy diffusion of 0.001 m^{2}.s^{-1}.

12. SEPA has established that a copepodid density over 0.75 individuals per m^{2} during one day is considered harmful to smolts migrating through the area [SEPA_Pers_comm_2022]. This risk evolves with time so the threshold for 2 days is 0.375, for 3 days 0.25, etc. Thus, all the maps are displayed with densities ranging from 0 to 0.75, giving a visual cue about the risk of harm for migrating salmon smolts.

Note that the sea lice densities predicted by this model have not been validated against field sampling of sea lice on wild fish.

6 Salmon lice model results

6.1 Farm biomass and production cycles

Three separate years were considered to cover a range of production cycles and their influence on salmon lice infestation. The years were 2017, 2018 and 2019 and all active farms across the West Coast of Scotland were included. Figure 6.1 shows the location of the proposed farm at Little Colonsay together with the 3 active farms in the vicinity, Gometra, Tuath and Geasgill, during the period 2017-2019.

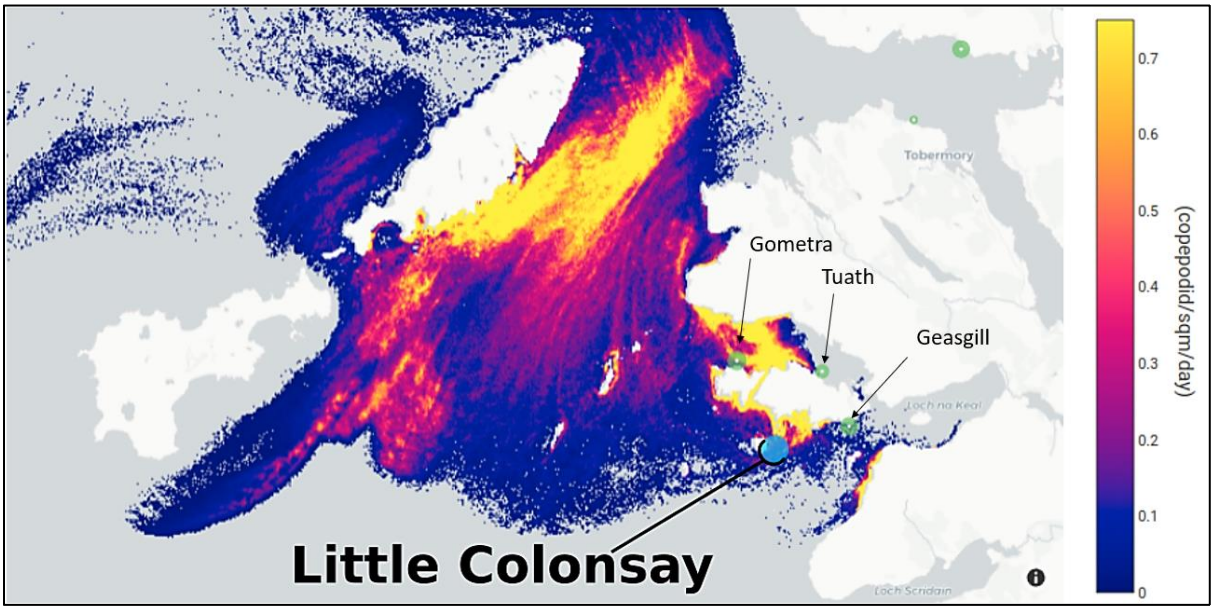

Figure 6.1 *Location of the proposed Little Colonsay farm shown by the blue circle. Other active farms in the area during the period 2017-2019 at Gometra, Tuath and Geasgill are shown as green circles. Image shows an example of average lice density contours. Note the densities above 0.75 copepodid/m^2/day in the Tiree Passage where salmon smolts have been tracked (https://atlanticsalmontrust.org/our-work/the-west-coast-tracking-project/).*

6.2 Salmon lice density heat maps

At the start of the calculation there are no salmon lice in the model so their density is zero. Salmon lice take several days to mature into infective copepodids, so the copepodid population gradually approaches a steady state, balanced between lice maturing and dying as shown in Figure 6.2. The 31-day period was chosen to be in May, the most likely month for post-smolt migration

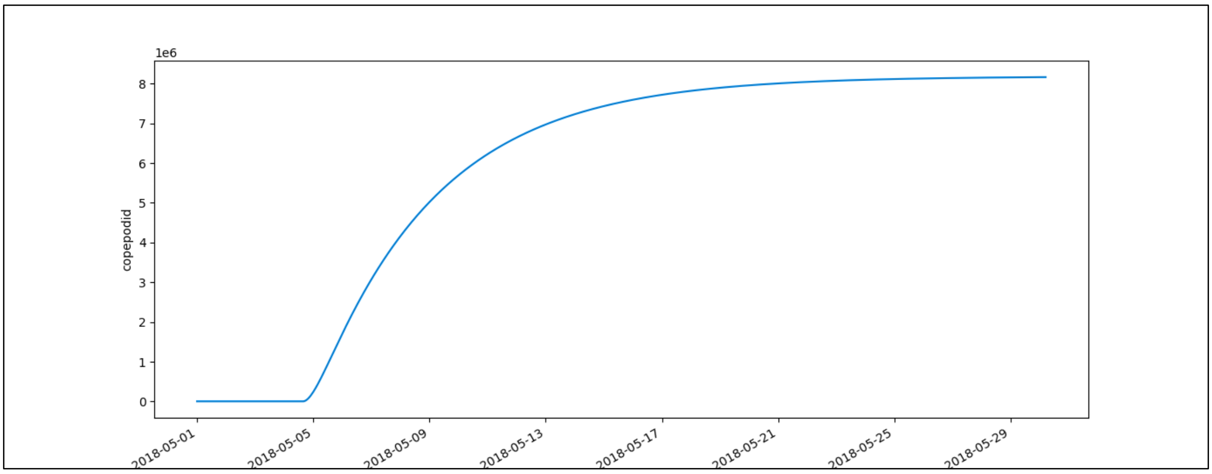

Figure 6.2 *Evolution of infective copepodids throughout the 31-day experiment from 1st -31st May 2018.*

When the biological model is integrated with the hydrodynamic model, salmon lice numbers evolve within each "super-individual" particle. This enables salmon lice densities to be calculated by summing the number of copepodids represented by all the particles in a given area. The particles are dimensionless, so the resulting density figures depend on the choice of spatial scale as well as on the time scale. A proper estimation of the risk to wild fish should not integrate too much data at large distances away from the particles, so higher resolutions will produce more detailed heat maps. All the maps are displayed with a 50m resolution. In addition, if too few particles are released per hour, the choice of sampling grid sizes can alter the apparent lice densities. The 50 super individual particles released per hour in our model is above the release rates from most published models. The results presented in figures 6.3 - 6.5 show the average copepodid densities. The heat maps show the average lice density (lice/m^2/day) based on particles present in any sampling cell over the period from when copepodids begin to appear (~4th May) until the 31st May.

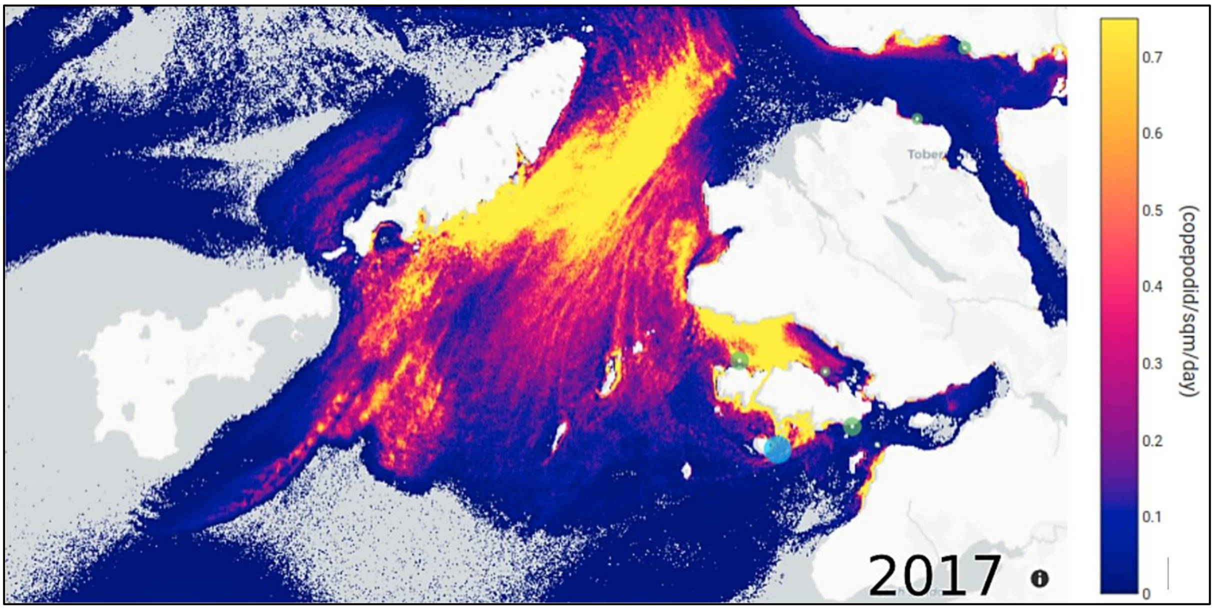

Figure 6.3 *Average salmon lice densities (copepodids.m^{-2}.day^{-1}) over 26 days (4th – 31st May 2017). Sampling grid spacing 50 m × 50 m. Blue circle is the Little Colonsay farm. Green circles show active farms for the year 2017. The size of each circle diameter gives an indication of the relative farm biomass (see* for further details)*. Grey areas indicate zones where no lice were encountered.*

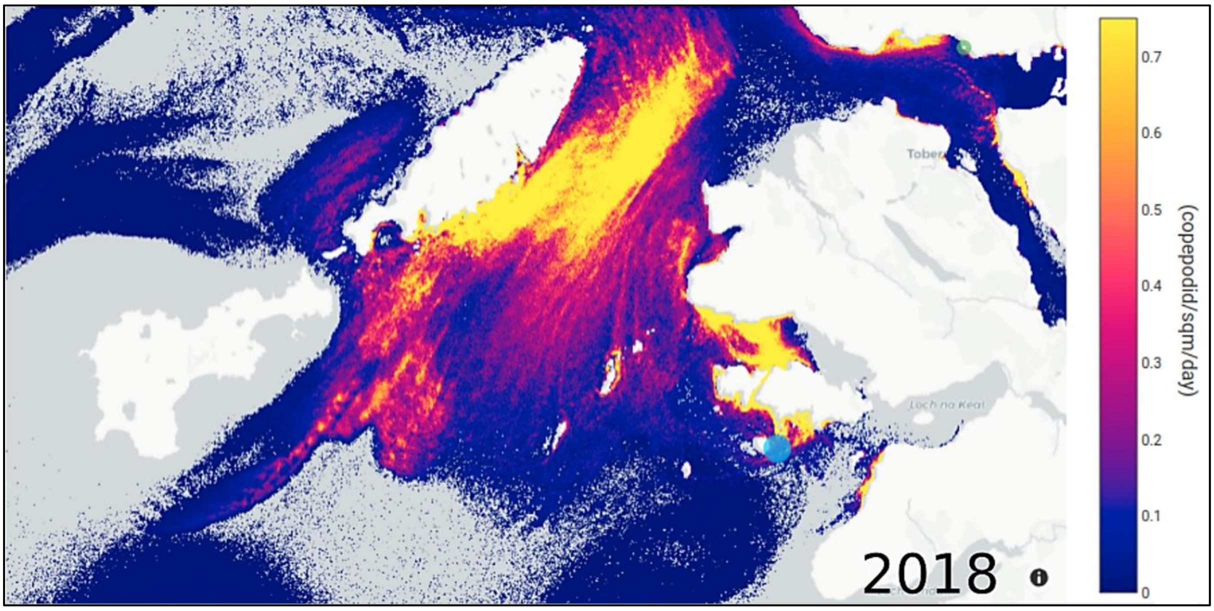

Figure 6.4 *Average salmon lice densities (copepodids.m^{-2}.day^{-1}) over 26 days (4th – 31st May 2018). Sampling grid spacing 50 m × 50 m. Blue circle is the Little Colonsay farm. Green circles show active farms for the year 2018. The size of each circle diameter gives an indication of the relative farm biomass (see* for further details)*. Grey areas indicate zones where no lice were encountered.*

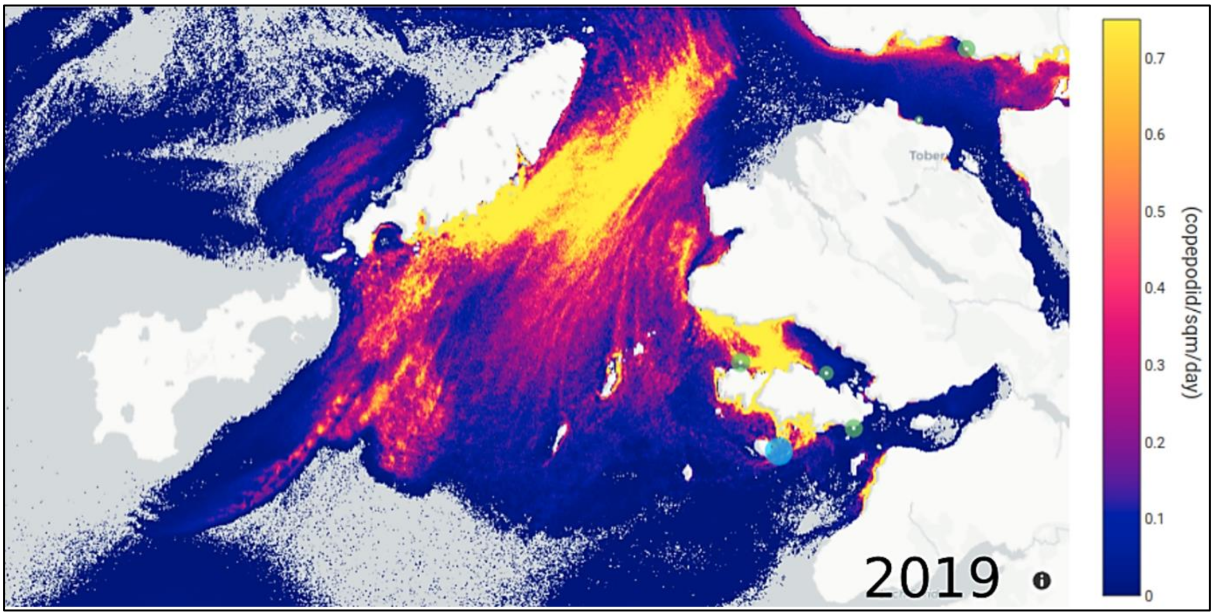

Figure 6.5 *Average salmon lice densities (copepodids.m^{-2}.day^{-1}) over 26 days (4th – 31st May 2019). Sampling grid spacing 50 m × 50 m. Blue circle is the Little Colonsay farm. Green circles show active farms for the year 2019. The size of each circle diameter gives an indication of the relative farm biomass (see* for further details)*. Grey areas indicate zones where no lice were encountered.*

Processing the salmon lice density transient evolution at high spatial and temporal resolution is rarely carried out due to computational limitations. However, in this study, we had the capacity to process animations of the salmon lice density at 50 m and 1-hour resolutions. Figure 6.6 shows a snapshot of the animation for the contribution of Little Colonsay only to the salmon lice infestation. Figure 6.7 shows a snapshot of the animation for the combined contributions of Little Colonsay, Gometra, Tuath and Geasgill in May 2019. The videos highlight very focused pollution along tidal features with density above 75 copepodid/m^2/day, 2 orders of magnitude greater than the harmful threshold. All four videos can be found at https://drive.google.com/drive/folders/1FUDpV7M3bhYst6UFMqUdhc84xehQmcmi?usp=share_link and included those for the combined contributions of Little Colonsay, Gometra, Tuath and Geasgill during the years 2017, 2018 and 2019.

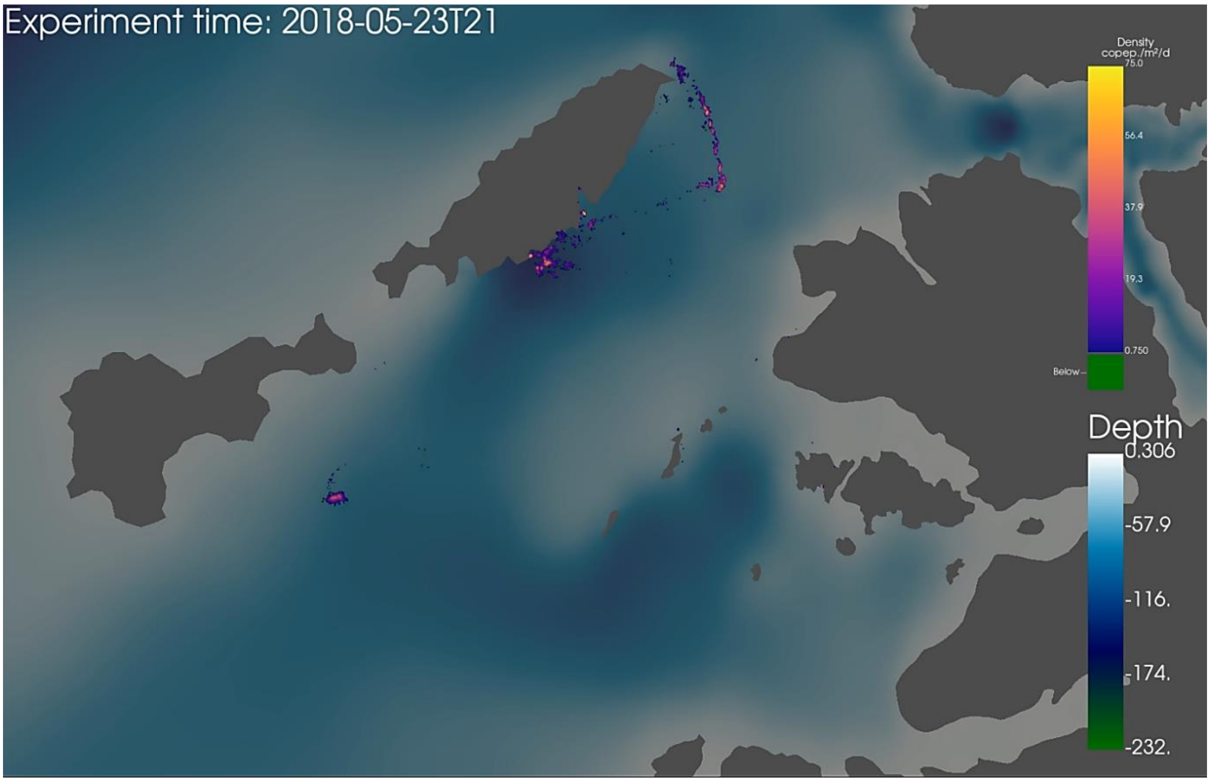

Figure 6.6 *Snapshot of the animation on the 23rd May 2018 at 21 h for the contribution of Little Colonsay only to the salmon lice infestation.*

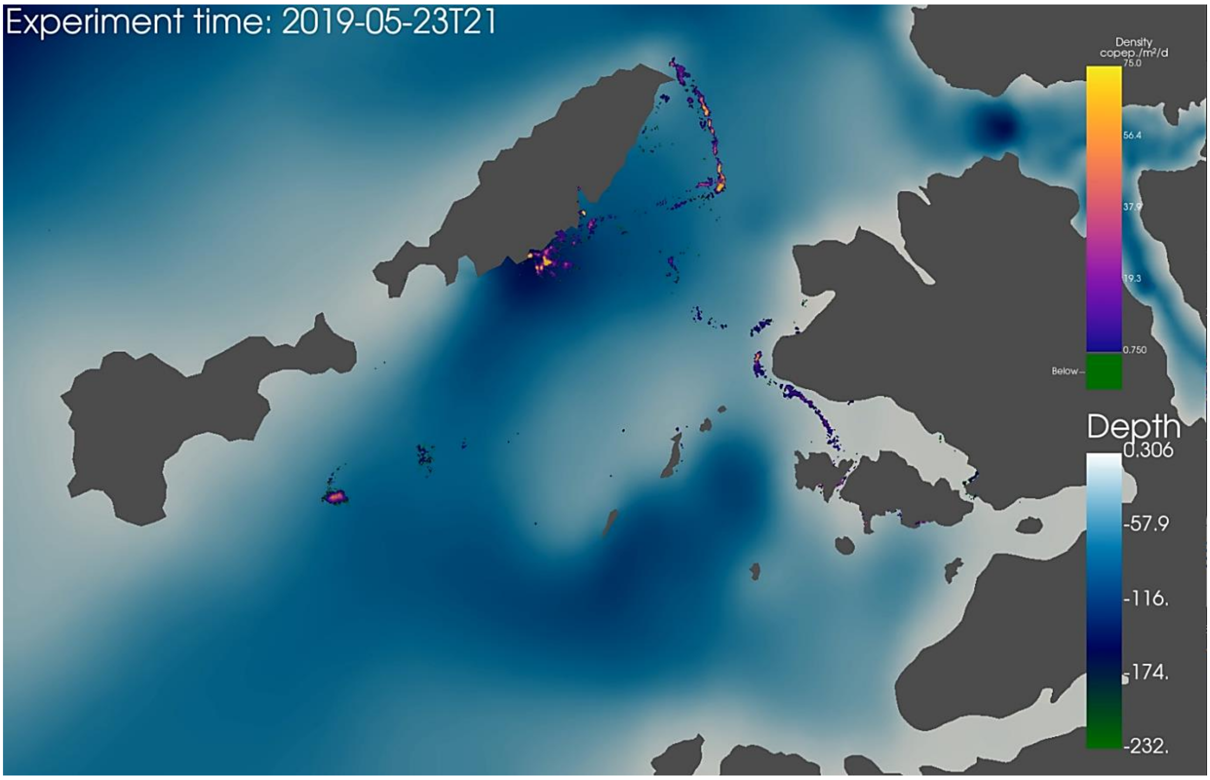

Figure 6.7 *Snapshot of the animation on the 23rd May 2019 at 21 h for the combined contributions of Little Colonsay, Gometra, Tuath and Geasgill.*

6.3 Discussion of results

The combined hydrodynamics-salmon-lice model has captured peak values and sharp gradients of lice density that are consistent with hydrodynamic features, such as tidal fronts. Such fronts may manifest themselves, for example, as line streaks to the north of the Treshnish isles as shown in Figures 6.3 to 6.5.

For May 2018, in the vicinity of Little Colonsay, only Gometra is stocked with a very low biomass of 126 tonnes as it is almost completely harvested. This means that the effects of lice infestation in the surrounding inner seas will be dominated by the 2773 tonnes proposed biomass at Little Colonsay. Figure 6.4 shows that peak values of 0.75 copepodids.m^{-2}.day^{-1} or greater are found to the north and south of Ulva and Gometra and in the Tiree Passage. Such a lice distribution is a direct consequence of the proposed farm at Little Colonsay.

In general, the average lice heat maps for 2017, 2018 and 2019 show that peak values of 0.75 copepodids.$m^{-2}day^{-1}$ or greater are likely to occur in the inner seas to the north and south of Ulva and Gometra and in the Passage of Tiree. Wild salmon and sea trout migrating to sea or returning to the river Ba through Loch Na Keal are likely to encounter lice densities of 0.75 copepodids.m^{-2}.day^{-1} or greater. Such areas represent zones of likely greater risk to local wild fish.

In addition, salmon smolts migrating from further afield are using the Passage of Tiree to reach the North Atlantic (*https://atlanticsalmontrust.org/our-work/the-west-coast-tracking-project/*). These smolts would be exposed to a high density after having passed through other affected areas during several days. The tracking data shows a salmon taking 4 days to go from the rivers to the western side of the Sound of Mull. According to the Salmon Trust preliminary results, smolts from the river Orchy are observed going through the Tiree Passage, passing South of the Isle of Mull, a journey that will take probably nearly a week. According to SEPA the exposure threshold for harm during 3 days is 0.25 copepodids.$m^{-2}day^{-1}$. Looking at their calculation, the threshold over a week should be under 0.1 copepodids.$m^{-2}day^{-1}$ (0.75/7). For these smolts, the proposed farm would constitute a significant threat to their migration as the salmon lice density is significantly higher than 0.1 particularly in the zone of influence of proposed Little Colonsay farm (Fig. 6.8).

High temporal resolution data in the animations show that salmon-lice concentrations can reach extreme levels (75 copepodids/m^2/day) locally during the month of May when the smolts are migrating (Figs. 6.6 and 6.7). The encounter with such a tidal front infestation would most likely eliminate any chance of survival of the smolts. Along these mixing fronts, the whole food chain accumulates as they are rich in nutrients triggering plankton blooms [Simpson_&_Sharples_2012]. The encounter between smolts and such zones is not directly documented at specie level but could be considered likely for fish in general requiring motive transport by currents or food.

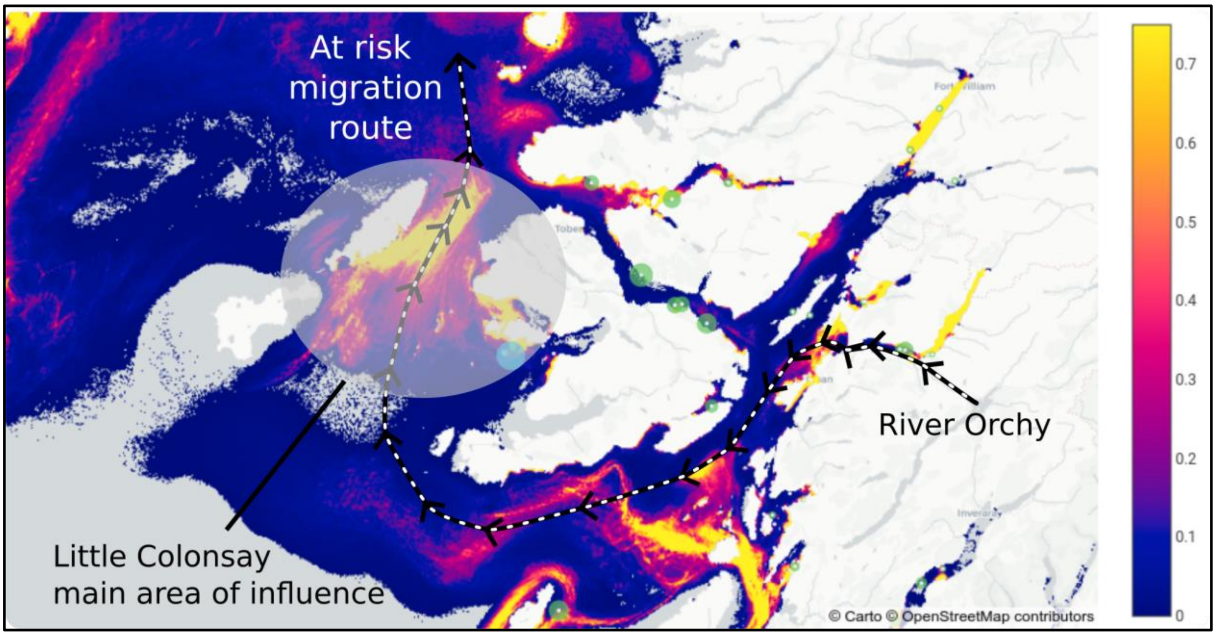

Figure 6.8 *Salmon-lice density map from 2018 including all the west-coast fish farms and the planned Little Colonsay farm. In 2018, the main area of influence would be represented by the grey circle. The several days-long migration route this area of high infestation affects is indicated by the arrows. On such a long route an acceptable density should be largely under 0.25 copepodids/m^2/day. Hence the addition of the Little Colonsay would represent a significant additional risk for salmon smolt migrating through the Passage of Tiree.*

7 Conclusions

- Bakkafrost is proposing a new fish farm site at Little Colonsay, Scotland. To support salmon-lice dispersion studies and their impact on wild fish, MTS-CFD was commissioned to develop a 3D HD model of the area. The HD model simulates water levels and flows (i.e., currents and tides) at spatial and temporal scales not possible from direct measurements.
- A coupled salmon-lice transport model has been developed which contains biological parameters for production, maturity, destruction and behavioural cues in terms of salinity, light and temperature, based on published scientific literature.
- The HD model correctly simulates the propagation of the tide within West Coast and Little Colonsay areas and provides an overall reasonable description of the general circulation within the inner seas at Little Colonsay.
- 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 salmon lice dispersion and an assessment of both the near-field and far-field dispersion effects.

- Average salmon lice heat maps show that peak values of 0.75 copepodids.$m^{-2}day^{-1}$ or greater are likely to occur in the inner seas to the north and south of Ulva and Gometra and in the Passage of Tiree. Such areas represent zones of likely greater risk to wild fish.
- Instantaneous values from high temporal resolution data in animations show that salmon-lice concentrations can reach extreme levels (75 copepodid/m^2/day) locally during the month of May when smolts are migrating.
- When displaying salmon-lice density figures, the choice of time scale and spatial scale can make a profound difference to the impression of risk to wild fish. Aggregations of salmon lice due to hydrodynamic features may produce areas of very high salmon-lice density.

References

[Adams_2012], Adams, T., Black, K.D., MacIntyre, C., MacIntyre, I., Dean, R. *Connectivity modelling and network analysis of sea lice infection in Loch Fyne, west coast of Scotland*, AQUACULTURE ENVIRONMENT INTERACTIONS, Vol. 3: 51–63, 2012. doi: 10.3354/aei00052

[Adams_2016], Adams, T.P., Aleynik, D., Black, K.D., *Temporal variability in sea lice population connectivity and implications for regional management protocols*, AQUACULTURE ENVIRONMENT INTERACTIONS, Vol. 8: 585–596, 2016. doi: 10.3354/aei00203

[Asplin_2020], Asplin, L. *et al.*, *The hydrodynamic foundation for salmon lice dispersion modelling along the Norwegian coast*, Ocean Dynamics, 2020 https://doi.org/10.1007/s10236-020-01378-0.

[Blue_Kenue_2023], https://nrc.canada.ca/en/research-development/products-services/software-applications/blue-kenuetm-software-tool-hydraulic-modellers - accessed 10th January 2023.

[DOSC_2023], https://digimap.edina.ac.uk/marine - accessed January 9th 2023.

[Bricknell_2006], Bricknell IR, Dalesman SJ, O'Shea B, Pert CC, Modue Luntz AJ. *Effect of environmental salinity on sea lice Lepeophtheirus salmonis settlement success*. Dis Aquat Org. 2006; 71: 201±212. https://doi.org/ 10.3354/dao071201 PMID: 17058601.

[Edwards_1986], Edwards, A. and Sharples, F., *Scottish Sea Lochs: A Catalogue*, 1986.

[Egbert_2002], Egbert, G.D. and Erofeeva S.Y. "Efficient inverse modeling of barotropic ocean tides." Journal of Atmospheric and Oceanic Technology 19.2 (2002): 183-204.

[ERA, 2023], https://cds.climate.copernicus.eu/ - accessed 9th January 2023.

[G2G_2018], Bell *et al*., *The MaRIUS-G2G datasets: Grid-to-Grid model estimates of flow and soil moisture for Great Britain using observed and climate model driving data.* https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/gdj3.55

[Heuch_2001], Heuch, P. A., Nordhagen, J. R. and Schram, T. A., *Egg production in the salmon louse [Lepeophtheirus salmonis (Krøyer)] in relation to origin and water temperature*, 24 December 2001, https://doi.org/10.1046/j.1365-2109.2000.00512.x

[Hill_1997], Hill, AE., Horsburgh, KJ., Garvine, RW., Gillibrand, PA., Slesser, G., Turrell, WR., & Adams, RD. *Observations of a density-driven recirculation of the Scottish coastal current in the Minch*. Estuarine Coastal and Shelf Science, 45(4), 473-484, 1997, https://doi.org/10.1006/ecss.1996.0198

[Johnsen_2014], Johnsen, I. A. *et al.*, 2014, *Vertical salmon lice behaviour as a response to environmental conditions and its influence on regional dispersion in a fjord system*, AQUACULTURE ENVIRONMENT INTERACTIONS, Vol. 5: 127–141, 2014 doi: 10.3354/aei00098.

[Johnsen_2016], Johnsen, I. A. *et al.*, 2016, *Salmon lice dispersion in a northern Norwegian fjord system and the impact of vertical movements*, AQUACULTURE ENVIRONMENT INTERACTIONS, 99–116, 2016, doi: 10.3354/aei00162.

[Johnsen_2020], Johnsen, I. A., Harvey, A., Sævik, P. N., Sandvik, A. D., Ugedal, O.,A˚ dlandsvik, B., Wennevik, V., Glover, K. A., and Karlsen, Ø. *Salmon lice induced mortality of Atlantic salmon during post-smolt migration in Norway.* – ICES Journal of Marine Science, 2020, doi:10.1093/icesjms/fsaa202.

[Launder_1974], Launder, B.E., Spalding, D.B. (March 1974). *The numerical computation of turbulent flows*, Computer Methods in Applied Mechanics and Engineering. 3 (2): 269–289. doi:10.1016/0045-7825(74)90029-2.

[Marine_Scotland_2012]*, Clyde Ecosystem Review*. Scottish Marine and Freshwater Science Vol. 3 No. 4. June 2012. https://www.gov.scot/publications/scottish-marine-freshwater-science-volume-3-number-3-clyde-ecosystem/pages/3/ - accessed 10th Jan. 2023.

[MTS_CFD_hydro_LC, 2023], Scanlon, T. J., Casseau, V. and Stickland, M. T., *Modelling of the Proposed Salmon Farm at Little Colonsay, Part 1. Hydrodynamics*, 2023.

[Myksvoll_2018], Myksvoll MS, Sandvik AD, Albretsen J, Asplin L, Johnsen IA, Karlsen Ø, et al., (2018), *Evaluation of a national operational salmon lice monitoring system—From physics to fish*. PLoSONE 13(7): e0201338. https://doi.org/10.1371/journal.pone.0201338

[Murray_Gillibrand_pers_comm_2022], Personal communication with Sandy Murray (Marine Scotland) and Phillip Gillibrand (MOWI).

[Novales_Flamarque_2018], Novales Flamarique, I., Browman, H. I., Bélanger M., Boxaspen K., *Ontogenetic changes in visual sensitivity of the parasitic salmon louse Lepeophtheirus salmonis*. J Exp Biol. (2000), Jun;203(Pt 11):1649-57. PMID: 10804155

[Offshore_Energy_SEA_2021], Offshore Energy SEA, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/194342/OES_A3d_Water.pdf - accessed 10th June 2021.

[Sabatino_2016], Sabatino, A., O'Hara Murray, R.B., Hills, A., Speirs, D.C., Heath, M.R. *Modelling sea level surges in the Firth of Clyde, a fjordic embayment in south-west Scotland*. Nat. Hazards, Vol. 84, No. 3. July 2016

[Salama_2013], Salama, N.K.G., Collins, C.M., Fraser, J.G., Dunn, J., Pert, C.C., Murray, A.G. and Rabe, B. *Development and assessment of a biophysical dispersal model for sea lice*, Journal of Fish Diseases 2013, 36, 323–337. doi:10.1111/jfd.12065

[Salama_2016], Salama, N.K.G., Murray, A.G., and Rabe, B. *Simulated environmental transport distances of Lepeophtheirus salmonis in Loch Linnhe, Scotland, for informing aquaculture area management structures*, Journal of Fish Diseases 2016, 39, 419–428. doi:10.1111/jfd.12375

[Salama_2018], Salama, N.K.G., Dale, A.C., Ivanov, V.V., Cook, P.F., Pert, C.C., Collins, C.M., Rabe, B. *Using biological–physical modelling for informing sea lice dispersal in Loch Linnhe, Scotland*, Journal of Fish Diseases, 2018;41:901–919. doi: 10.1111/jfd.12693

[Samsing_2016], Samsing, F. *et al.*, 2016, *Salmon lice (Lepeophtheirus salmonis) development times, body size, and reproductive outputs follow universal models of temperature dependence*, Canadian Journal of Fisheries and Aquatic Sciences, 25 May 2016, https://doi.org/10.1139/cjfas-2016-0050.

[Sandvik_2020], Sandvik, A. D. *et al.*, *Prediction of the salmon lice infestation pressure in a Norwegian fjord*, ICES Journal of Marine Science, Volume 77, Issue 2, March 2020, Pages 746–756, https://doi.org/10.1093/icesjms/fsz256

[ScotGov_2021], https://www.gov.scot/publications/summary-of-information-relating-to-impacts-of-salmon-lice-from-fish-farms-on-wild-scottish-sea-trout-and-salmon/ - accessed 10th June 2021.

[SEPA, pers. comm. 2022] Sea lice exposure threshold and protection zones, stakeholder workshops, December 2022.

[SEPA_2023], https://www.sepa.org.uk/media/450279/regulatory-modelling-guidance-for-the-aquaculture-sector.pdf - accessed 9th January 2023.

[Simpson_1997], Simpson, J. H. and Hill, A. E., *The Scottish Coastal Current*, 1987, DOI: 10.1007/978-3-642-70886-2_21.

[Simpson_&_Sharples_2012], Tidal mixing fronts: their location, dynamics and biological significance. in: Introduction to the Physical and Biological Oceanography of Shelf Seas , pp. 233 - 265. DOI: https://doi.org/10.1017/CBO9781139034098.011 Publisher: Cambridge University Press.

[SSM_2023], http://www.marine.gov.scot/themes/scottish-shelf-model - accessed 9th January 2023.

[SSPO_2023], https://www.salmonscotland.co.uk/code-of-good-practice - accessed 10th January 2023.

[SWEERS_1976] Sweers, H. E., *Monograms to estimate the heat-exchange coefficient at the air-water interface as a function of wind speed and temperature; a critical survey of some literature*. Journal of Hydrology, 30:375–401, 1976.

[Scanlon_A, 2023], Scanlon, T. J., *A Hydrodynamic Model of the West Coast of Scotland – Validation Case Studies* https://claws-scot.github.io/reports/ - accessed 9th January 2023.

[Scanlon_B, 2023], Scanlon, T. J. and Casseau, V., CLAWS – Chemicals Lice and Waste from Salmon Farms, 1. Hydrodynamics Model. https://claws-scot.github.io/reports/ - accessed 9th January 2023.

[Stein_2005], Stein, A., Bjorn, P. A., Heuch, P. A. and Elston, D. A., *Population dynamics of salmon lice Lepeophtheirus salmonis on Atlantic salmon and sea trout*, April 2005, Marine Ecology Progress Series 290:263-275, doi:10.3354/meps290263.

[TELEMAC_2023], http://www.opentelemac.org/ - accessed 9th January 2023.

Time and Date (2021) https://www.timeanddate.com/weather/@2633500/historic?month=5&year=2019 – accessed 10th June 2021.

[UK_Crown_Estate_2023], Guerin, A.J., Jackson, A.C., Bowyer, P.A., Youngson, A.F. *Hydrodynamic models to understand salmon migration in Scotland*. London: The Crown Estate, 2014. Marine Research Report. https://eprint.ncl.ac.uk/file_store/production/211079/7EF9ADA9-3468-403F-AB56-9E45908002D8.pdf - accessed 9th January 2023.