Isle of Muck, CAR/L/1109999

Waste Solids & In-feed Medicine Deposition Modelling Report

Mowi Scotland Ltd.

March 2022

Mowi Scotland

OFFICE [redacted]

POSTAL [redacted]

PHONE +44

FAX -

MAIL [redacted]

WEB [redacted]

CONTENTS

List of Figures

List of Tables

EXECUTIVE SUMMARY

Model simulations have been performed to assess the likely deposition of waste solids and in-feed medicine at a salmon farm site near the Isle of Muck. This report explains the application of the NewDepomod model to describe the deposition of waste solids and in-feed medicine beneath the pens and in the surrounding environment. The modelling procedure followed as far as possible guidance presented by the Scottish Environment Protection Agency (SEPA) in January 2022 (SEPA, 2022). Modelling of the cumulative waste solids deposition from Muck together with deposition from nearby site at Rum and proposed site at Canna is also presented using a coupled hydrodynamic model with Mowi's in-house particle tracking model *unptrack* (Gillibrand, 2021).

Results indicated that deposition at Muck will be minimal, with a maximum deposition of 835.5 g m^{-2} (Table 1). The footprint area, where the deposition exceeded the critical deposition rate of 250 g m^{-2}, was 0.158750 km^2. The intensity of deposition, 414.9 g m^{-2} was less than the critical value of 2000 g m^{-2}. The results also confirm that the current consented amount of Emamectin Benzoate (EMBZ) of 1110 g can be used in the proposed layout.

These results indicate that the proposed new layout at Muck and biomass increase will comfortably meet pertinent Environmental Quality Standards for salmon farm waste solids. Cumulative modelling indicated that the deposited wastes from Muck will not interact with solid wastes discharged from the neighbouring site at Rum and proposed new site at Canna.

Table 1. Site details & summary of results

Site Details	
Site Name:	Muck
Site Location:	Isle of Muck
Peak Biomass (T):	4,069
Feed Load (T/year):	10,396
Pen Details	
Number of Pens:	8
Pen Dimensions:	160m Circumference
Working Depth (m):	15
Configuration:	2x4, 100m matrix
NewDepomod Results	
Allowable Mixing Zone (m^2):	177,099
Maximum Deposition (g m^{-2}):	835.5
Modelled Footprint (m^2):	158,750
Mean Footprint Deposition (g m^{-2}):	414.9

1 INTRODUCTION

This report has been prepared by Mowi Scotland Ltd. to describe the deposition of waste solids from a marine salmon farm near the **Isle of Muck** (Figure 1 and Figure 2). It explains the application of the NewDepomod model to describe the deposition of waste solids and in-feed medicine beneath the pens and in the surrounding environment. The modelling procedure followed as far as possible guidance presented by the Scottish Environment Protection Agency (SEPA) in January 2022 (SEPA, 2022). Modelling of the cumulative waste solids deposition from Muck together with deposition from nearby site at Rum and the proposed site at Canna is also presented using a coupled hydrodynamic model with Mowi's in-house particle tracking model *unptrack* (Gillibrand, 2021).

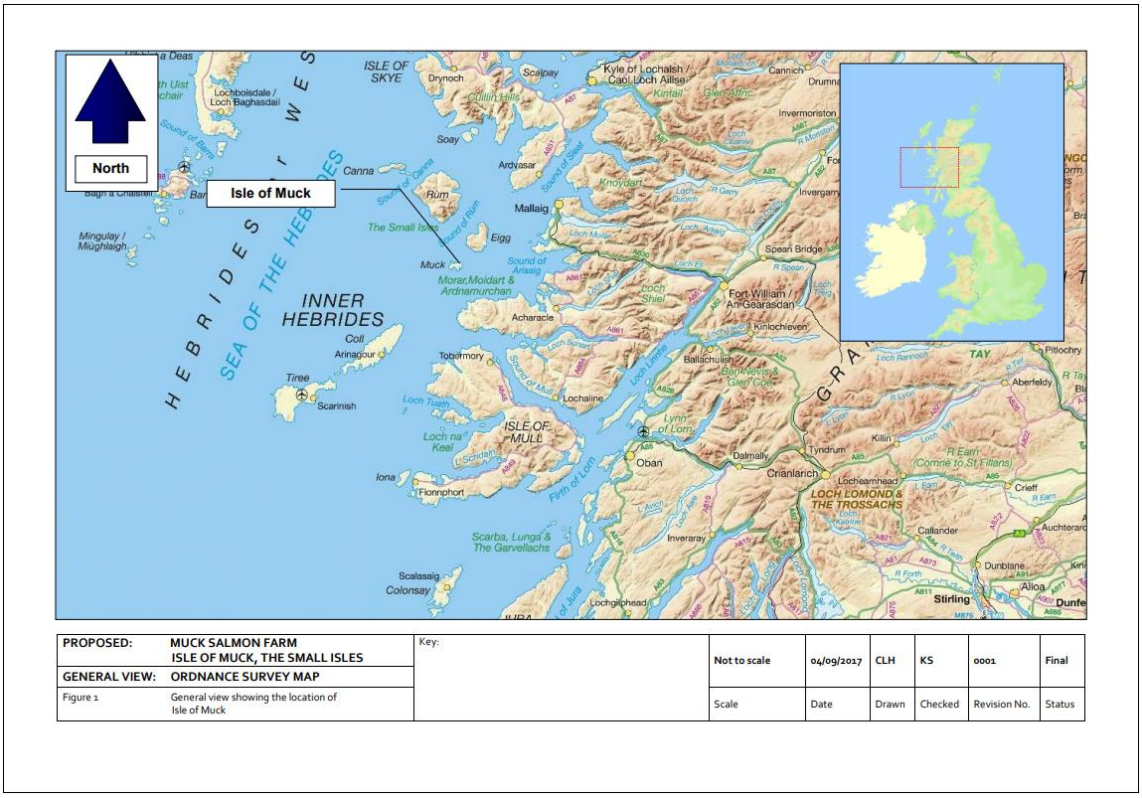

Figure 1. Location of the Isle of Muck Site

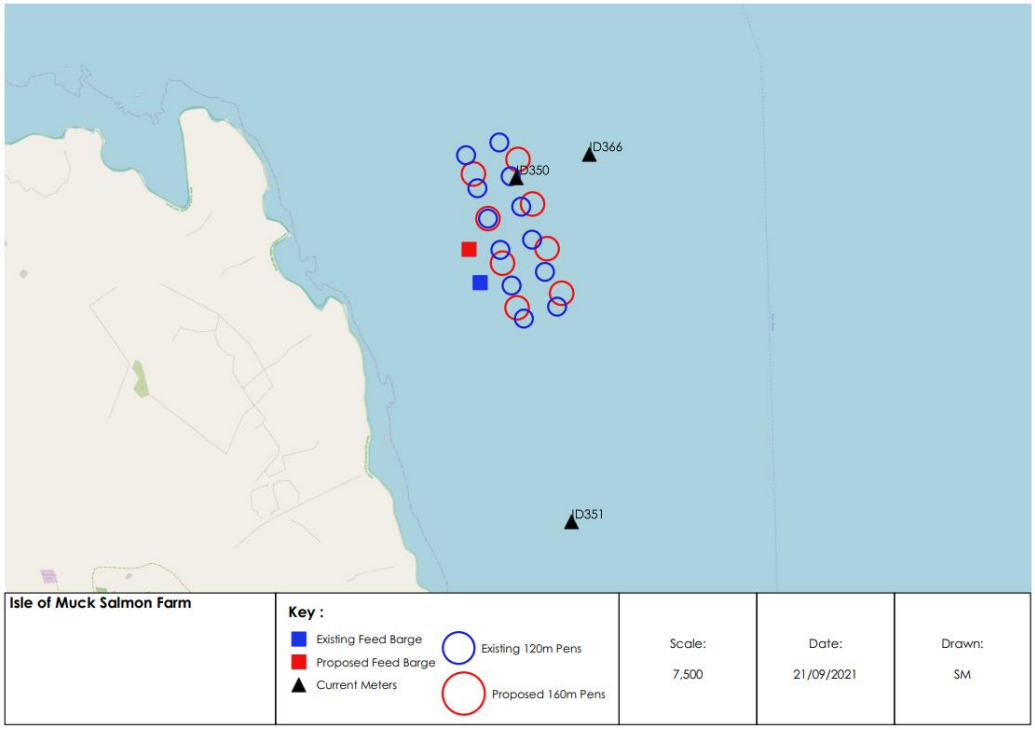

Figure 2. Existing (blue) and proposed (red) layouts at the Isle of Muck salmon farm. ADCP deployment locations are also marked with a black triangle

Table 2. Summary of hydrographic data from near bed currents

Hydrographic Summary	ID350	ID366
Deployment Date	Apr-May 2010	Jan-Apr 2021
Easting	143198	143354
Northing	780484	780534
Mean Speed (m/s)	0.128	0.142
Residual Speed (m/s)	0.005	0.065
Residual Direction (°G)	333	006
Tidal Amplitude Parallel (m/s)	0.193	0.197
Tidal Amplitude Normal (m/s)	0.063	0.073
Major Axis (°G)	330	350

1.1 Site Details

The existing site is situated off the East of the Isle of Muck (Figure 1 and Figure 2). Details of the site and hydrographic summary are provided in Table 1 and Table 2. The receiving water is defined as open water. The pen centre locations are given in Table 3. These locations were used in the computer modelling (Section 2).

Table 3. Details of the individual pen centre locations and net depths used in the modelling for Muck.

Cage	Easting	Northing	Net Depth (m)
1	143200	780207	15
2	143295	780238	15
3	143169	780302	15
4	143264	780333	15
5	143138	780397	15
6	143233	780428	15
7	143107	780492	15
8	143202	780525	15

The most recent benthic monitoring survey at the Muck site was conducted in March 2020. It has been classified as 'Satisfactory' by SEPA, confirming compliance with both pen edge and mixing zone environmental standards. Figure 3 shows the sample stations which are colour coded for either above or below an IQI value of 0.64. Section 2.1 describes the significance of this value.

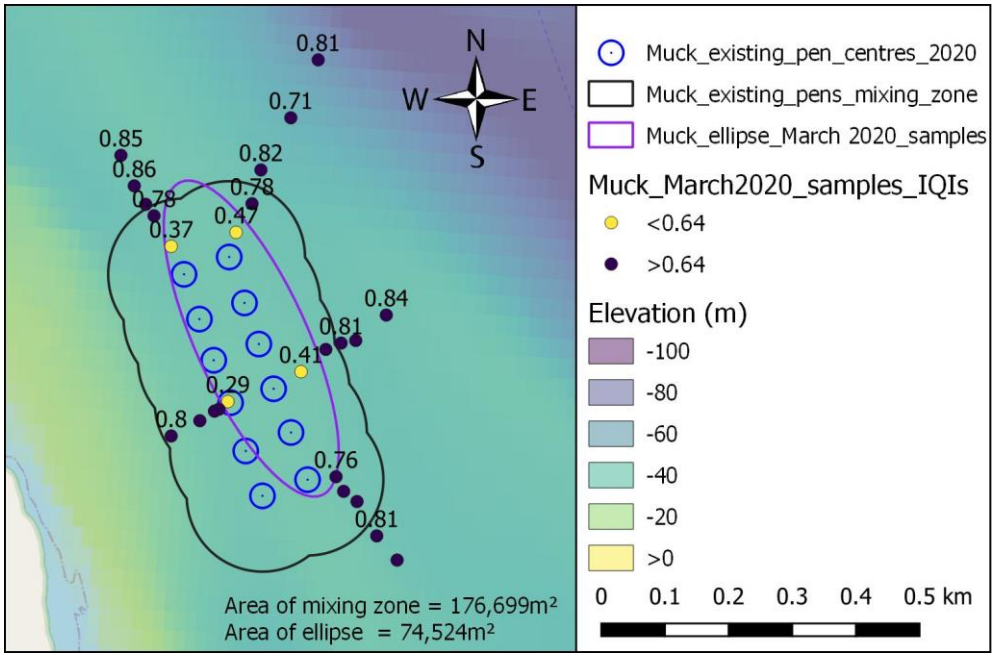

Figure 3. Sampling stations for the Muck 2020 benthic monitoring survey. IQI values are shown and colour coded (yellow < 0.64 IQI and black > 0.64 IQI)

2 MODEL DETAILS

Three sets of simulations were performed. The first and second set focussed on localised deposition of waste solids and in-feed medicine beneath the proposed 160m pens and utilised the NewDepomod model, configured in the default parameter values specified by SEPA and using measured flow data to force the model. The third set investigated the cumulative deposition arising from the site at Muck together with that from neighbouring Small Isles site at Rum and the proposed site at Canna; for this set, flow fields from a hydrodynamic model, RiCOM, were used to force a particle tracking deposition model, *unptrack*.

2.1 Local Deposition: NewDepomod

NewDepomod is a bespoke modelling software designed to simulate the dispersion of particulate wastes from salmon farms. The model (SAMS, 2021) has been developed by the Scottish Association for Marine Science (SAMS) and is supplied under licence. The version used for the modelling described here was:

library version:
numerics version: Final 1.20211021113834.1634811708
datatypes version: Final 1.20211021113826.1634811708
util version: v1.4.0-rc02-(SEPA)

A regular model grid was prepared. The grid covered a 2km x 2km area, with a 25m grid spacing in both directions. The grid size was 80 x 80 cells. The water depth was 35.6 m, the weighted average of the depths at the two current meter deployments (ID350 and ID366). The flowmetry file combined the data from ID350 and ID366; after merging the length of the combined record was 97 days in total.

A larger grid (3km x 4km) was prepared for the Emamectin Benzoate modelling. The same grid spacing and water depth was used.

2.1.1 Waste Feed and Faeces

The model was configured exactly as specified by SEPA in the modelling guidance published in January 2022 (SEPA, 2022). The site was modelled for a maximum biomass of 4069 tonnes with a feed load of 7 kg/tonne/day. This configuration of the model produces a conservative estimate of the benthic footprint, with a deposition rate of 250 g m^{-2} equating approximately to an Infaunal Quality Index (IQI) of 0.64 (the boundary between moderate and good status). Work by SEPA has shown that footprints predicted by this “standard default” configuration broadly match the footprint area derived from seabed samples, although there is a great deal of variability from site to site.

Following the standard default approach, NewDepomod was used to simulate one year of deposition at the maximum farm biomass. Results were analysed over the final 90 days of the simulation, with the mean deposition rate across the model domain being calculated and the footprint area being delimited by the 250 g m^{-2} contour (SEPA, 2022). The results are presented in Section 3.1.

2.1.2 In-feed Medicine Modelling

Muck salmon farm has a current EMBZ consent of 1110g. To check that the proposed 8 x 160m pens do not negatively impact the deposition, the in-feed medicine model of New-Depomod was used. It was run for 118 days, with hourly results over the final two days (Days 116 – 118) saved to file. This approach followed that of the standard default modelling approach outlined in the SEPA Regulatory Modelling Guidance (SEPA 2022). The mean concentrations of Emamectin Benzoate were calculated from this output for comparison with the EQS value of 11.75 ng/kg (wet weight, equivalent to 23.5 ng/kg dry weight), which is the current interim position standard.

2.2 Cumulative Deposition: Hydrodynamic and Particle Tracking Models

The cumulative deposition modelling approach utilised a coupled hydrodynamic and particle tracking method, whereby water currents in the region, modelled using a calibrated hydrodynamic model, advected particles representing waste solids around the model domain. Deposition from existing sites at Muck and Rum was modelled as well as deposition from the proposed site at Canna.

The hydrodynamic modelling approach is described in full in the accompanying report (Mowi, 2022) and is only summarised here. Flow fields were calculated using RiCOM (River and Coastal Ocean Model). RiCOM is a general-purpose hydrodynamics and transport model, which solves the standard Reynolds-averaged Navier-Stokes equation (RANS) and the incompressibility condition, applying the hydrostatic and Boussinesq approximations (Walters and Casulli, 1998). It has been tested on a variety of benchmarks against both analytical and experimental data sets. The model has been previously used to investigate the inundation risk from tsunamis and storm surge on the New Zealand coastline, the effects of mussel farms on current flows, and, more recently in Scotland to study tidal energy resource and the effects of energy extraction on the ambient environment (McIlvenny et al., 2016; Gillibrand et al., 2016b).

The mathematical equations are discretized on an unstructured grid of triangular elements which permits greater resolution of complex coastlines, such as typically found in Scotland. Therefore greater spatial resolution in near-shore areas can be achieved without excessive computational demand.

For the particle tracking component, Mowi's in-house model "*unptrack*" (Gillibrand, 2021) was used. The model used the hydrodynamic flow fields from the RiCOM model simulations. This model has been used previously to simulate sea lice dispersal (Gillibrand & Willis, 2007), the development of a harmful algal bloom (Gillibrand et al., 2016a) and the dispersion of cypermethrin from a fish farm (Willis et al., 2005). The approach for particulate wastes is the same as for living organisms, except that medicine has no biological behaviour but instead has a prescribed settling velocity: numerical particles represent either waste feed pellets or faecal waste. Particles are released continuously at pen locations, with initial particle positions distributed randomly through the pen volumes. The particles are then subject to advection, from the modelled flow fields, and horizontal and vertical diffusion. The prescribed settling velocity means particles rapidly settle onto the seabed, from where they can be resuspended back into the water column if the seabed stress exceeds a critical value, or where they may remain in place.

2.2.1 Model Domain and Boundary Conditions

The unstructured mesh used in the modelling was adapted from the mesh used by Gillibrand et al (2016b) (Figure 4). This domain was chosen so that the open boundary would be further away from the site of interest than is the case with the Marine Scotland ECLH and WLLS domains. Model resolution was enhanced in the Small Isles region, particularly around the Mowi site at Muck (Figure 5). The spatial resolution of the model varied from 25m in some inshore waters to 20km along the open boundary. The model consisted of 119,925 nodes and 231,016 triangular elements. Bathymetry was taken from the European Marine Observation and Data Network (EMODnet, Figure 6 and Figure 7).

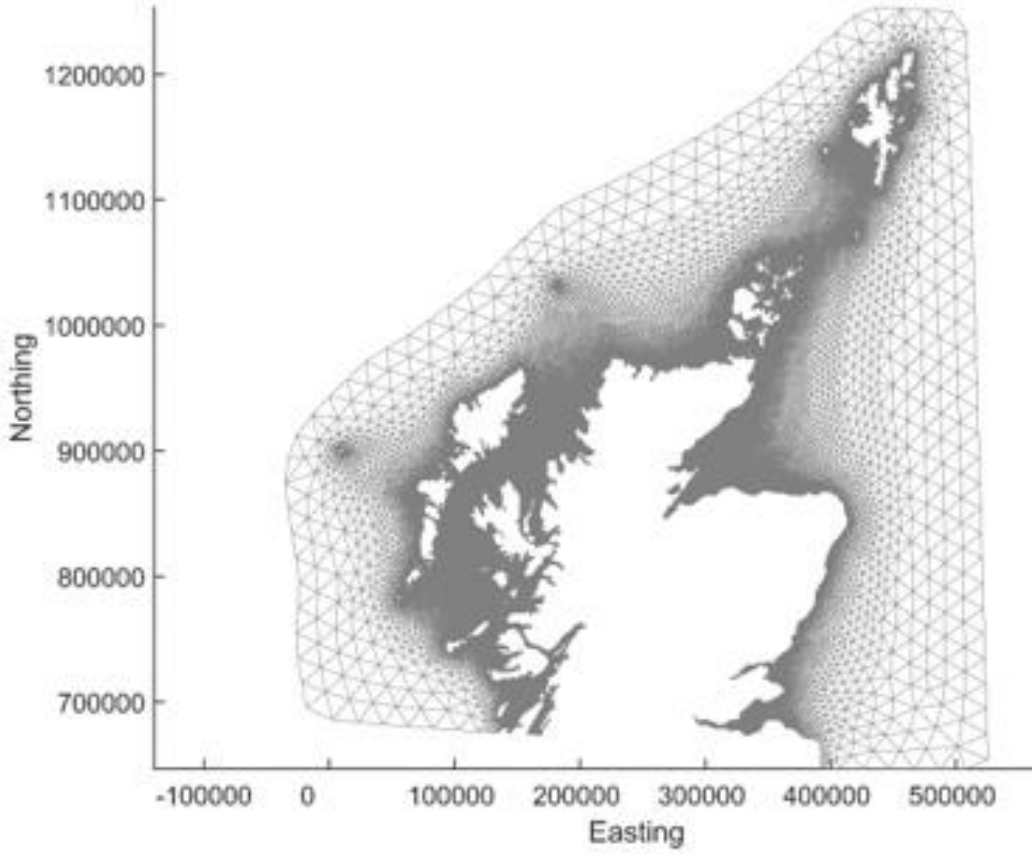

Figure 4. The mesh and domain of the modelling study, adapted from Gillibrand et al (2016b).

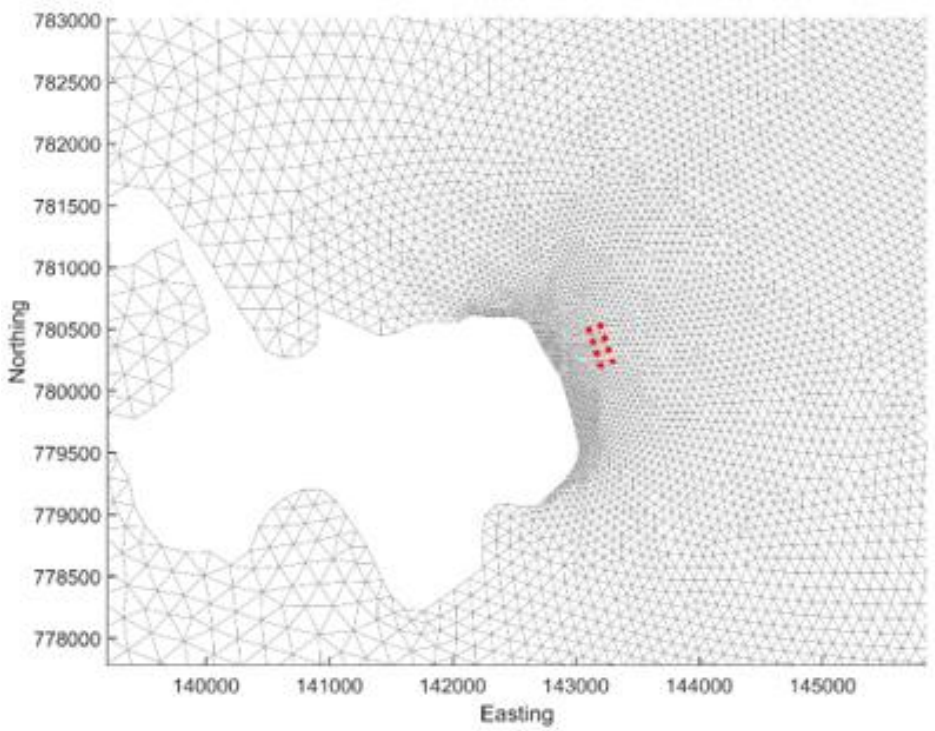

Figure 5. The unstructured mesh around the Muck site in the modified model grid, with the proposed pen locations indicated (○)

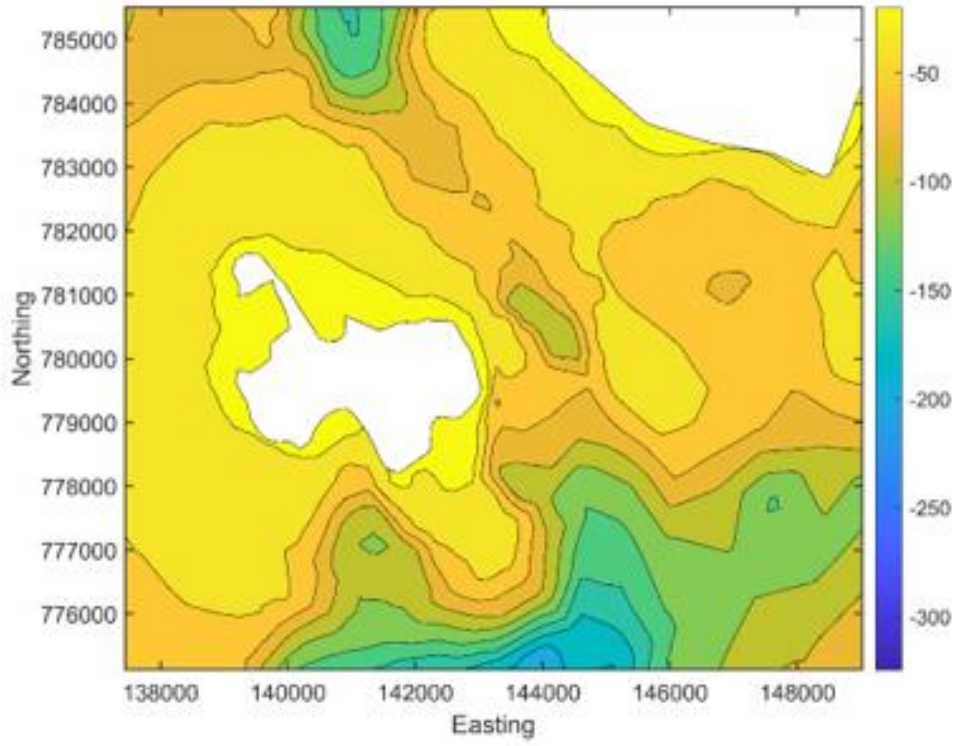

Figure 6. Localised bathymetry (m) around Muck from the modified model.

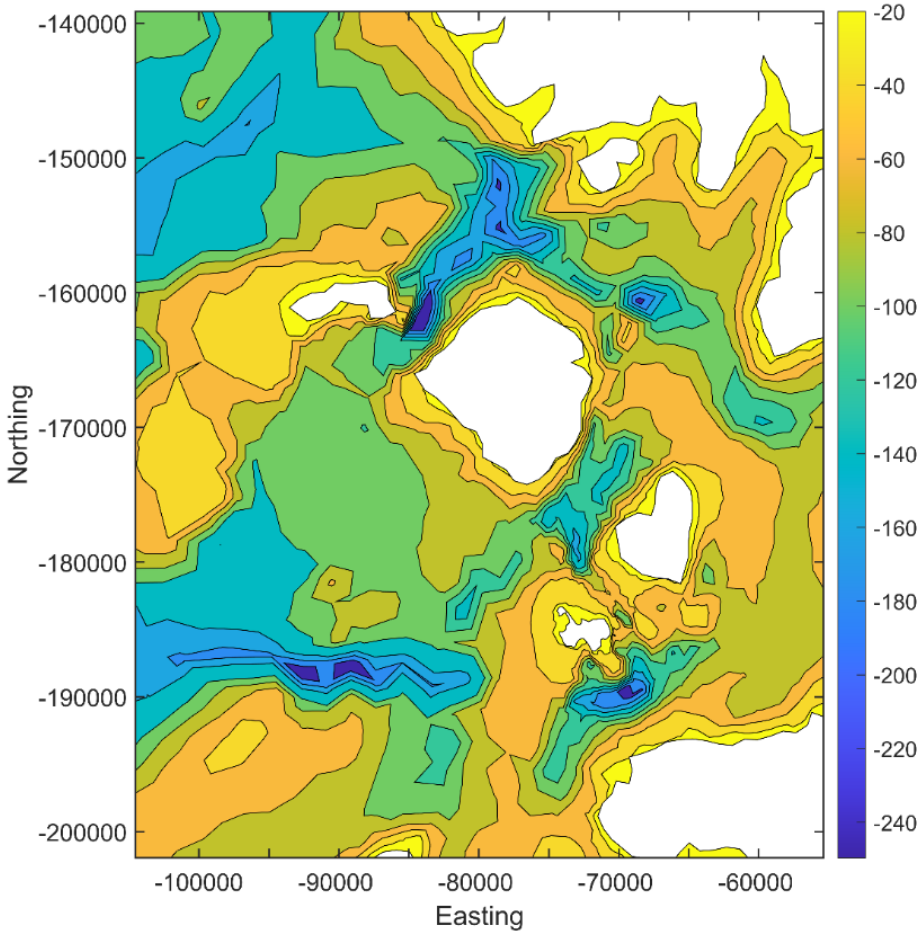

Figure 7. Localised water depths (m) around the Small Isles in the modified model domain.

The model was forced at the outer boundaries by eight tidal constituents (O_1, K_1, P_1, Q_1, M_2, S_2, N_2, K_2) which were taken from the Scottish Shelf Model (Marine Scotland, 2016). Spatially- and temporally-varying wind speed and direction data are taken from the ERA5 global reanalysis dataset (ECMWF, 2021) for the required simulation periods.

Stratification is relatively weak in this location, given the strong tidal flows in the area, and the model was run in 2D vertically-averaged mode.

Full details of the calibration and validation of the hydrodynamic model are given in the Hydrodynamic Model Description (Mowi Scotland Ltd, Muck Hydrodynamic Model Description, 2022).

2.2.2 Hydrodynamic Model Calibration

The RiCOM model has previously been calibrated against sea level and current meter data from the north of Scotland (Gillibrand et al. 2016b). For the current study, the model was further calibrated and validated against hydrographic data collected in the region of the farm site from 2010 and 2021. The data are described in the relevant hydrographic reports. In April 2010, an

Acoustic Doppler Current Profiler (ADCP) workhorse was deployed close to the farm site (Figure 2 & Table 2) until May 2010 (ID350). A second deployment, ID351, was collected during the same time period as ID350, also using an ADCP workhorse. A third deployment, ID366, was collected between January 2021 and April 2021 with an ADCP. The ADCP deployments provided both current velocity and seabed pressure data which were used to calibrate and validate modelled velocity and sea surface height.

The following main simulations were performed, corresponding with the dates of the ADCP deployments:

1. 8th April 2010 – 19th May 2010 (ADCP deployment ID350)
2. 8th April 2010 – 19th May 2010 (ADCP deployment ID351)
3. 27th January 2021 – 15th April 2021 (ADCP deployment ID366)

The calibration process and results are described fully in the accompanying hydrodynamic modelling report (Mowi, 2022).

2.2.3 Particulate Waste Deposition Modelling

The particulate deposition modelling, performed using the *unptrack* model (Gillibrand, 2021), simulated the settling of waste solids (waste feed and faeces) discharged from pens during a production cycle. In addition to the pens at Muck, wastes were released from the site at Rum and the proposed site at Canna at the consented/proposed biomass (Table 4) with pen locations at Rum and Canna given in Table 5. Particles were discharged continuously, with each numerical particle representing 5 kg of particulate waste. Feed and faecal particles were assigned settling velocities within the range of 0.095 m s^{-1} ±10% and 0.032 m s^{-1} ± 10% respectively, the same as the values used by NewDepomod. The particle tracking model used the simulation from January – April 2021 (ID366) as this was the longest hydrodynamic model run, at 79 days.

Table 4. Modelled biomass and feed rate for the cumulative modelling

Sites	Modelled Biomass (T)	Feed Rate (kg/T/day)
Muck	4069	7
Rum	3500	7
Canna	2500	7

Table 5. Pen centre locations for the Rum and Canna sites used in the modelling

	Rum		**Canna**	
Pen	Easting	Northing	Easting	Northing
1	140875	803046	128371	805494
2	140938	803005	128283	805514
3	141001	802964	128391	805581
4	141127	802883	128303	805602
5	141190	802842	128411	805669
6	141252	802801	128323	805689
7	140916	803109	128431	805757
8	140979	803068	128343	805777
9	141042	803027		
10	141167	802946		
11	141230	802905		
12	141293	802864		

When a particle reaches the seabed due to its settling velocities, it may be resuspended into the water column and be subject again to advection and diffusion. Resuspension is modelled using a stochastic approach, whereby a probability of resuspension is specified for each settled particle every time step. In the present simulations, the probability of resuspension, P, was calculated by:

$$P = c_r(\tau_b - \tau_{bc})e^{-t/\lambda}$$

where $\tau_b = \rho u_*^2$ is the bed shear stress derived from the local modelled current speed, τ_{bc} is the minimum critical shear stress required to erode particles off the seabed, c_r is a resuspension constant, and λ is a consolidation time scale. With this approach, the probability of particle erosion decreases as particles age, as it becomes more likely that the particle is consolidated into the seabed sediment. The parameters c_r, τ_{bc} and λ are tunable coefficients that can be used to calibrate the deposition model. A bed roughness scale of z_0 = 0.01 m was used to calculate the bed shear stress from the local current speed.

3. RESULTS

3.1 Local Deposition: NewDepomod

3.1.1 Waste Feed and Faeces

The modelled footprint for the Muck farm using the SEPA standard default method is shown for the proposed biomass (Figure 8). The area of the footprint, as defined by the deposition rate of 250 g m^{-2}, was 158,750 m^2 (Table 6). The maximum 90-day mean deposition was 835.5 g m^{-2}. The intensity of deposition was 414.9 g m^{-2} which is well below the critical value of 2,000 g m^{-2}.

These results indicate that the proposed equipment change and biomass increase will comfortably meet pertinent Environmental Quality Standards for salmon farm waste solids.

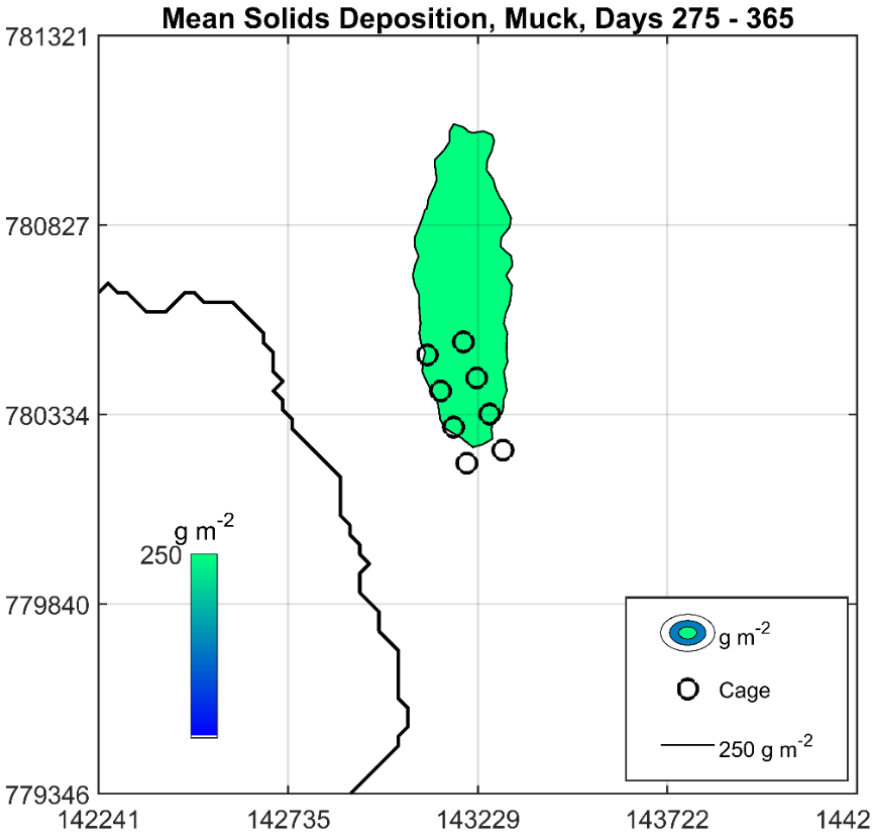

Figure 8. The modelled footprint for Muck for the proposed biomass increase of 4069 tonnes, using the SEPA standard default method.

Table 6. The modelled footprint area and mean footprint deposition for Muck for the proposed biomass increase, using the SEPA standard default method.

NewDepomod Results Summary	
Maximum Biomass (T)	4,069
Feed Load (T/year)	10,396
Solid Waste Release Rate (kg/day)	4548.74
Allowable Mixing Zone (m^2)	177,099
Maximum Deposition (g m^{-2})	835.5
Modelled Footprint (m^2)	158,750
Mean Footprint Deposition (g m^{-2})	414.9

3.1.2 In-feed Medicine Modelling

The in-feed medicine model of NewDepomod was run using both the existing layout of 12 x 120m pens and the proposed 8 x 160m pens. This was done to determine whether the change in equipment would have an effect on the deposition shown from the site with the current consented EMBZ mass of 1110g. The results show that the proposed layout does not increase the EMBZ footprint by more than the allowed 15% (Table 7), with a marginal increase well within the bounds of model variability.

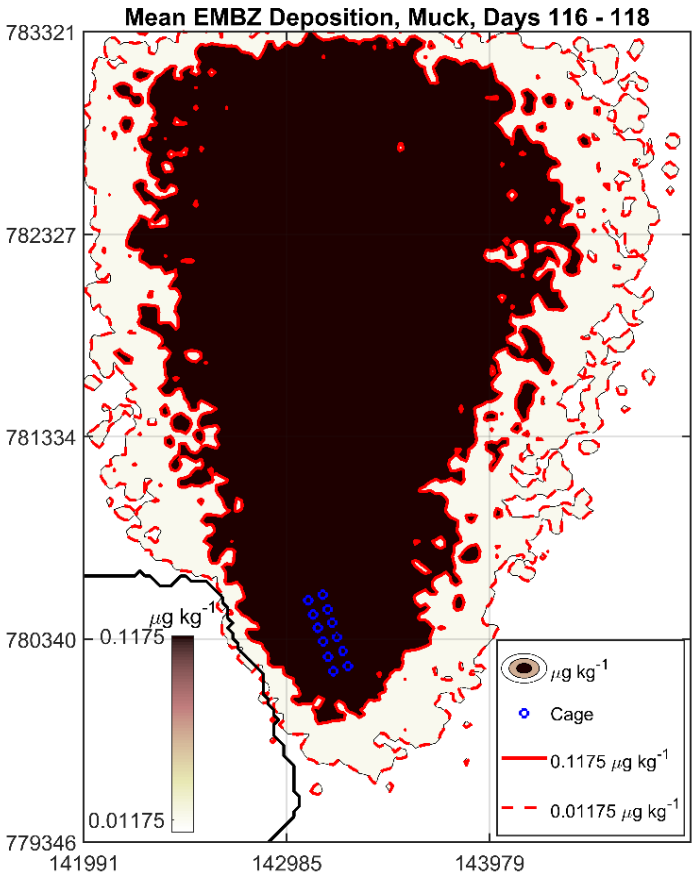

Figure 9: Predicted mean Emamectin Benzoate deposition over days 116 – 118 for the existing 12 x 120m pens at Muck following a consented treatment of 1110g.

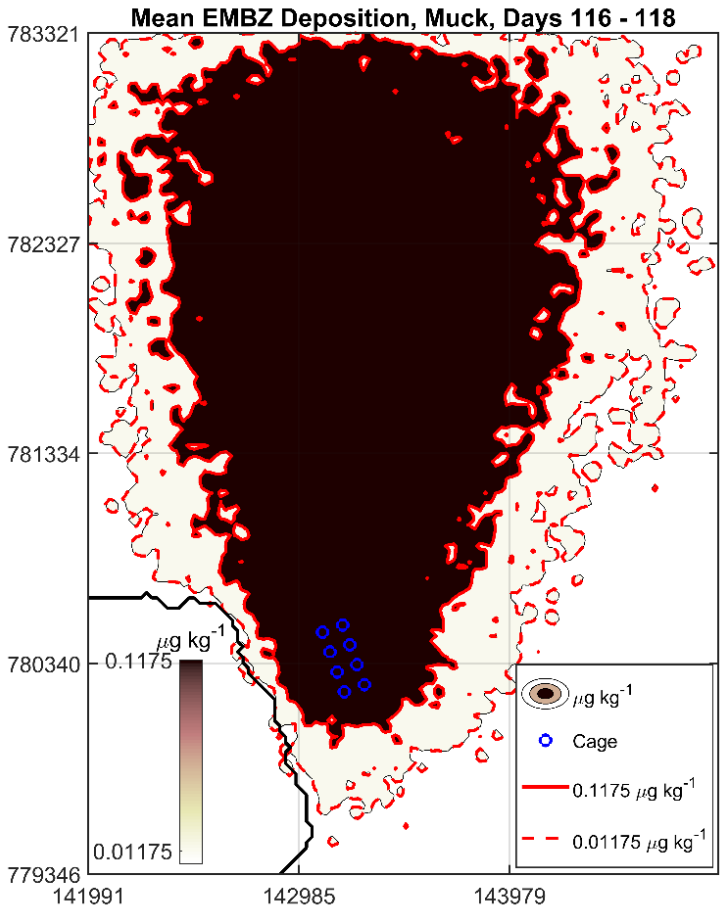

Figure 10: Predicted mean Emamectin Benzoate deposition over days 116-118 for the proposed 8 x 160m pens at Muck following a consented treatment of 1110g.

Table 7: Percentage change in EMBZ footprint areas (km^2) from the existing and proposed pen layouts at Muck following a consented treatment of 1110g.

Layout	Area > 0.01175 ug/kg (km^2)	Area > 0.1175 ug/kg (km^2)
Existing	7.288	4.769
Proposed	7.380	4.809
% change	+1.26%	+1.26%

3.2 Cumulative Predictions for the Small Isles

Cumulative particulate deposition arising from all three Small Isles sites was modelled using the maximum consented (or proposed) biomass at each site and the nominal feed rate (Table 4). Deposition was modelled for 365 days, and the mean deposition over the final 90 days calculated (Figure 11 and Figure 12). The results indicate that, as expected due to the dynamic nature of the sites, very small footprints (deposition exceeding 250 g/m^2) at all three sites were predicted. These results also confirm that the deposition footprints do not interact with each other.

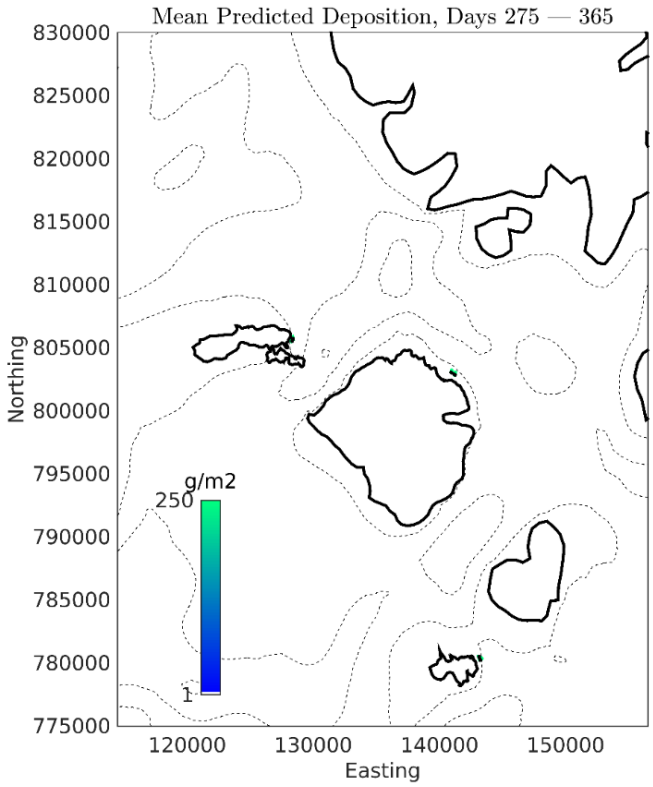

Figure 11. Predicted mean solids deposition over 90 days from the sites at Rum, Muck and the proposed site at Canna using the nominal feed rate (7 kg/tonne/day) at each site.

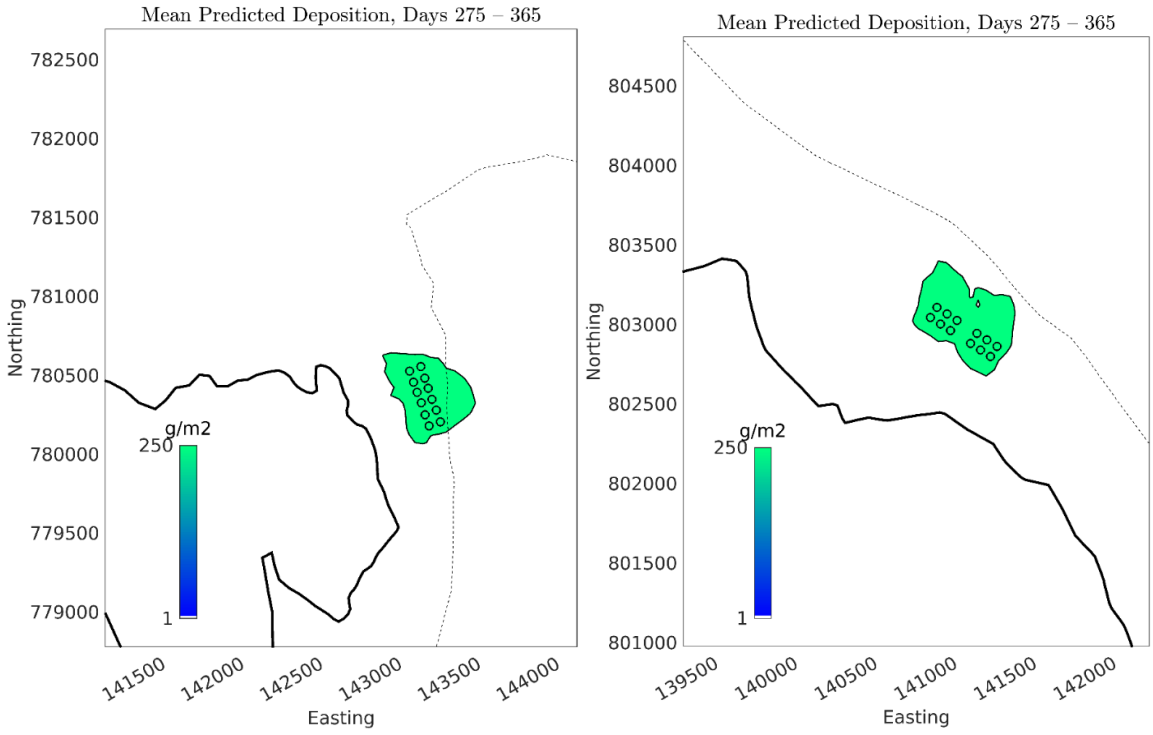

Figure 12. Modelled deposition footprints from the cumulative modelling at Muck (left) and Rum (right).

4. SUMMARY AND CONCLUSIONS

The biomass of 4069 tonnes requested for consent at the Muck site, and the associated feed loading (Table 8), has been shown to comfortably meet pertinent Environmental Quality Standards. The SEPA standard default method, which is designed to provide a conservative prediction of particulate deposition, suggested no significant deposition will occur at the site, meeting both mixing zone and deposition intensity criteria. The cumulative modelling also indicates that deposition from Muck will not interact with deposition from neighbouring sites at Rum and Canna.

The results indicated that the change in equipment from 12 x 120m pens to 8 x 160m pens will not significantly increase the EMBZ footprint size, with a predicted increase of only 1.26%, well within the bounds of model variability.

Table 8. Summary of Results

Site Details	
Site Name:	Muck
Site Location:	Isle of Muck
Peak Biomass (T):	4,069
Feed Load (T/year):	10,396
Pen Details	
Number of Pens:	8
Pen Dimensions:	160m Circumference
Working Depth (m):	15
Configuration:	2x4, 100m matrix
NewDepomod Results	
Allowable Mixing Zone (m^2):	177,099
Maximum Deposition (g m^{-2}):	835.5
Modelled Footprint (m^2):	158,750
Mean Footprint Deposition (g m^{-2}):	414.9

5. REFERENCES

European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/bathymetry-0

Gillibrand, P.A., 2021. *Unptrack* User Guide. Mowi Scotland Ltd., September 2021, 32 pp.

Gillibrand, P.A., B. Siemering, P.I. Miller and K. Davidson, 2016a. Individual-Based Modelling of the Development and Transport of a Karenia mikimotoi Bloom on the North-West European Continental Shelf. Harmful Algae, DOI: 10.1016/j.hal.2015.11.011

Gillibrand, P.A., Walters, R.A., and McIlvenny, J., 2016b. Numerical simulations of the effects of a tidal turbine array on near-bed velocity and local bed shear stress. *Energies*, vol 9, no. 10, pp. 852. DOI: 10.3390/en9100852

Gillibrand, P.A. and K.J. Willis, 2007. Dispersal of Sea Lice Larvae from Salmon Farms: A Model Study of the Influence of Environmental Conditions and Larval Behaviour. Aquatic Biology, 1, 73-75.

Marine Scotland, 2016. Scottish Shelf Model. Part 1: Shelf-Wide Domain. Available at https://data.marine.gov.scot/dataset/scottish-shelf-model-part-1-shelf-wide-domain

McIlvenny, J. , Tamsett, D., Gillibrand, P.A. and Goddijn-Murphy, L., 2016. Sediment Dynamics in a Tidally Energetic Channel: The Inner Sound, Northern Scotland. Journal of Marine Science and Engineering, 4, 31; doi:10.3390/jmse4020031

Mowi, 2022. Muck Hydrodynamic Model Description Report. Mowi Scotland Ltd, February 2022.

Scottish Association for Marine Science (SAMS), 2021, NewDEPOMOD Modelling Software. https://depomod.sams.ac.uk

SEPA, 2022. Interim Marine Modelling Guidance for Aquaculture Applications. Scottish Environment Protection Agency, Air & Marine Modelling Unit, 25th January 2022.

Walters, R.A.; Casulli, V., 1998. A robust, finite element model for hydrostatic surface water flows. Comm. Num. Methods Eng., 14, 931–940.

Willis, K.J, Gillibrand, P.A., Cromey, C.J. and Black, K.D., 2005. Sea lice treatments on salmon farms have no adverse effect on zooplankton communities: A case study. *Marine Pollution Bulletin*, 50, 806 – 816.