Marine Aquaculture Site Loch Hourn

Appendix 3. Waste Solids Deposition Modelling

Mowi Scotland Limited
November 2021

[redacted]

Waste Solids Deposition Modelling

CREAG AN SAGAIRT, LOCH HOURN

Mowi Scotland Limited

CAR/L/1105276/V

October 2021

[redacted]

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EXECUTIVE SUMMARY

This report has been prepared by Mowi Scotland Ltd. to meet the requirements of the Scottish Environment Protection Agency (SEPA) for an application to install equipment, increase production and for consent to use in-feed sealice treatments on a marine salmon farm at **Creag an Sagairt** in **Loch Hourn**, via NewDepomod modelling. This report describes waste solids and in-feed medicine modelling results for the Creag an Sagairt site, a summary of which is provided in Table 1 below. The approach applied NewDepomod using both the SEPA standard default method and a calibrated approach using benthic data from four seabed surveys. The calibrated model indicates that the proposed biomass will not breach the allowable mixing zone area. The SEPA standard default method, which appears to predict the intensity of deposition better than the footprint area for this site, indicates that the lower stocking density proposed in this application will improve the pen edge deposition rates.

Table 1. Summary of Results

SITE DETAILS			
Site Name:		Creag an Sagairt	
Site location:		Loch Hourn	
Peak biomass (T):		3,100	
Proposed feed load (T/yr):		7920.5	
CAGE DETAILS			
Number of cages:		8	
Cage dimensions:		160m Circumference	
Working Depth (m):		20	
Cage group configuration:		1 x 8, 100m matrix	
HYDROGRAPHIC SUMMARY			
		ID246	**ID254**
Surface Currents	Average Speed (m/s)	0.066	0.043
	Residual Direction (°G)	330	326
	Wind-Influence	Strong	Strong
Middle Currents	Average Speed (m/s)	0.053	0.039
	Residual Direction (°G)	335	307
Seabed Currents	Average Speed (m/s)	0.037	0.042
	Residual Direction (°G)	341	354
BENTHIC MODELLING			
Max fish biomass proposed (T)		3,100	
Max Average Stocking Density (kg/m³)		9.51	
IN-FEED TREATMENTS			
Recommended consent mass EmBZ (g)		2.1	
Equivalent Fish Biomass (T)		6.1	
Maximum Treatment Amount EmBZ (g)		2.1	

1. INTRODUCTION

This report has been prepared by Mowi Scotland Ltd. to meet the requirements of the Scottish Environment Protection Agency (SEPA) for an application to install equipment, increase production and for consent to use sufficient sealice treatments on a marine salmon farm at **Creag an Sagairt**, **Loch Hourn** via NewDepomod modelling. This report describes waste solids and in-feed medicine modelling results for the Creag an Sagairt site in Loch Hourn (Figure 1) to determine EQS-compliant biomass and sea-lice treatment levels for the proposed equipment. The modelling procedure follows the generic Method Statement provided to SEPA in June 2021 (Mowi, 2021).

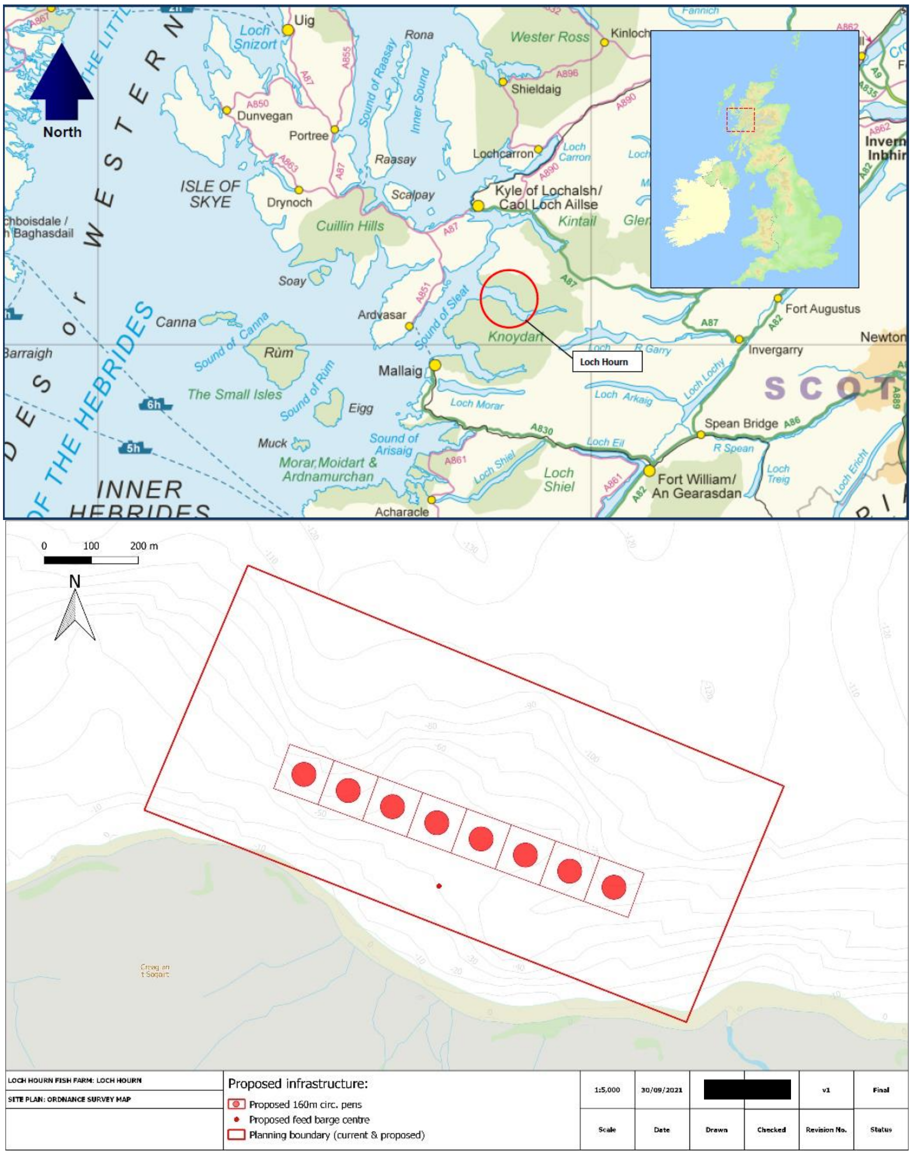

Figure 1. Location of the Creag an Sagairt salmon farm in Loch Hourn (top) and the proposed cage positions (bottom).

1.1 Site Details

The proposed site is situated on the southern shore of Loch Hourn (Figure 1). Mowi proposes to deploy eight 160m circumference pens and operate a maximum biomass of 3,100 tonnes. As such, the NewDepomod has been run to determine EQS-compliant biomass and in-feed medicinal consents for this new equipment. Details of the site are provided in Table 2. The receiving water is defined as a sea loch.

Table 2. Project Information

SITE DETAILS		
Site Name:	Creag an Sagairt	
Site location:	Loch Hourn	
Peak biomass (T):	3,100	
Proposed feed load (T/yr):	7,921	
Proposed treatment use:	Azamethiphos, Cypermethrin, Deltamethrin & **Emamectin Benzoate**	
CAGE DETAILS		
Group location:	NG803096	
Number of cages:	8	
Cage dimensions:	160m circumference	
Grid matrix (m)	100	
Working Depth (m):	20	
Cage group configuration:	1 x 8	
Cage group orientation (°G):	123.0°	
Cage group distance to shore (km):	0.24	
Water depth at site (m):	40 – 50 m	
HYDROGRAPHIC DATA		
	ID246	**ID254**
Current meter position:	179910, 809766	179909, 809751
Depth at deployment position (m):	32.02	34.50
Surface bin centre height above bed (m):	27.72	28.72
Middle bin centre height above bed (m):	16.72	18.72
Bottom bin centre height above bed (m):	3.72	3.72
Duration of record (days):	55	42
Start of record:	11-Sep-2018	29-Nov-2018
End of record:	05-Nov-2018	11-Jan-2019
Current meter averaging interval (min):	20	20
Magnetic correction to grid North:	-0.30605	-0.26605

2. SEABED DATA

Seabed surveys are conducted towards the end of every production cycle to ensure compliance with benthic environmental quality standards. These survey data have been used to calibrate and validate NewDepomod (§4). SEPA's Finfish Aquaculture Sector Plan, launched in 2019, required greater numbers of seabed samples to be taken during compliance surveys than were previously required. For Loch Hourn, during the seabed survey of December 2019, 35 benthic samples were taken, compared to 6 in 2017 and 11 – 12 in 2013 and 2015 (Table 3).

Table 3. Seabed samples collected since 2013

Production Cycle	Dates of Survey	Number of Samples
2012 – 2013	24th November 2013	12
2014 – 2015	14th – 15th December 2015	11
2016 – 2017	4th December 2017	6
2018 – 2019	14th – 16th December 2019	35

The greater number of samples collected in 2019, taken along four approximately perpendicular transects from the pens, allows an ellipse to be drawn where the benthic Infaunal Quality Index (IQI) falls below 0.64. The area of this ellipse must be less than the 100m mixing zone defined around the cage group.

The calculated ellipse for the 2018 – 2019 production cycle was 182,217 m^2 (Figure 2). The 100m mixing zone for the existing pen configuration is 217,017m^2. The ellipse area was therefore 84% of the allowable mixing zone. The site, following the 2018-2019 production cycle, was therefore compliant with environmental licence conditions.

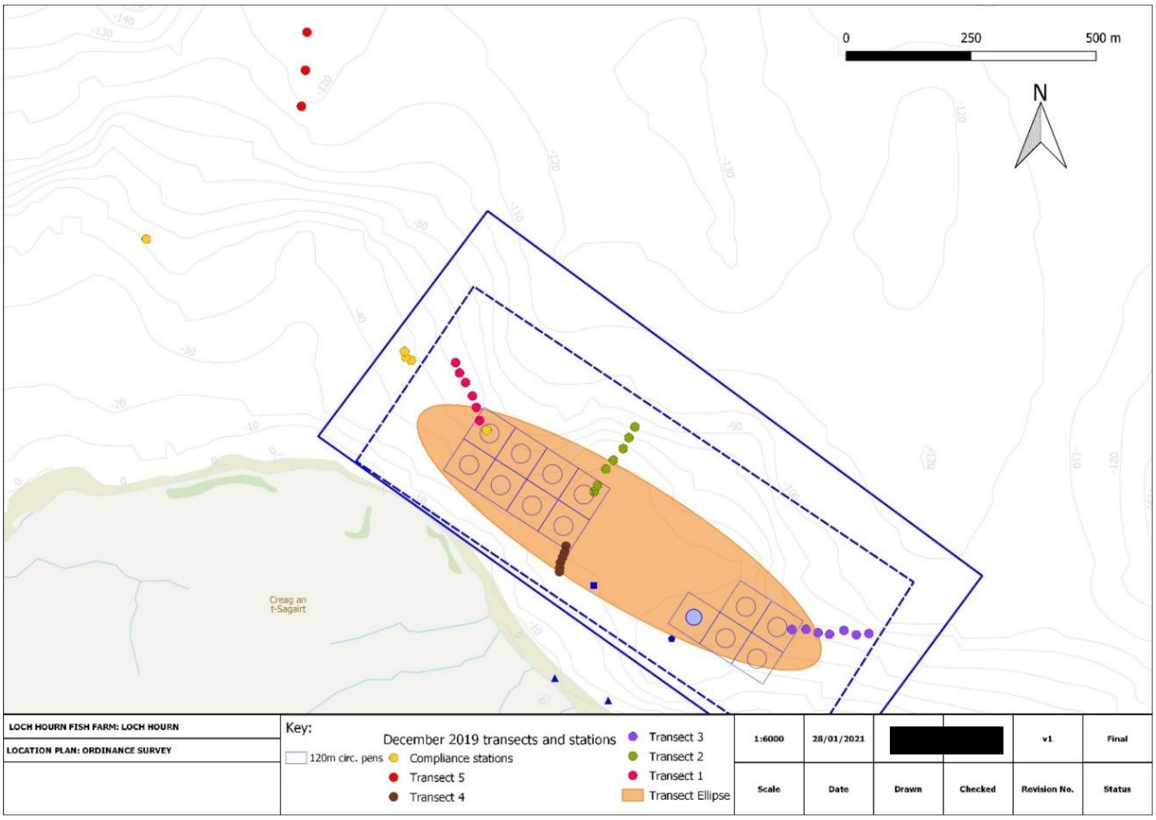

Figure 2. Sample locations (coloured circles) from the December 2019 seabed survey at Loch Hourn. The orange ellipse indicates the area where the measured IQI was below 0.64. Pens are indicated by the open circles (○).

3. MODEL DETAILS

Three sets of simulations were performed. The first two sets focussed on localised deposition beneath the proposed pens and utilised the NewDepomod model. The first set used NewDepomod configured in the standard default parameter values specified by SEPA and used measured flow data to force the model on a flat seabed. This approach is stipulated by SEPA and must be included in every application. The second set involved calibrating

NewDepomod against the 2019 seabed survey data, producing a parameter set that accurately predicted seabed impacts at the Creag an Sagairt site. The parameter set was then validated against the previous seabed survey data from 2013, 2015 and 2017. In this method, realistic bathymetry was used, and NewDepomod was forced by flow fields from a hydrodynamic model. The third set of simulations investigated the cumulative deposition arising from the proposed site at Creag an Sagairt together with that from neighbouring sites in Loch Nevis, Loch Duich and Loch Alsh. For this third set, flow fields from the same hydrodynamic model were used to force a different particle tracking deposition model, unptrack. All models are described in the sections below.

3.1 Local Deposition: NewDepomod Standard Default Method

NewDepomod is bespoke modelling software designed to simulate the dispersion of particulate wastes from salmon farms. The model (https://www.sams.ac.uk/science/projects/depomod/) 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 1.20201028152741.1603895684
datatypes version: Final 1.20201028152733.1603895684
util version: v1.3.1-final-(SEPA)

The model was configured exactly as specified by SEPA in the modelling guidance published in July 2019 (SEPA, 2019). The site was modelled for a maximum biomass of both 2500 tonnes and 3100 tonnes, with a feed load of 7 kg/tonne/day applied. This configuration of the model produces a conservative estimate of the benthic footprint, with a deposition rate of 250 g m^{-2} thought to equate 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. The model is capable of making more accurate predictions of seabed impact when it is calibrated against seabed IQI data from previous production cycles (see §3.2).

A regular model grid was prepared. The grid covered an area of 2.5 km x 1.5 km area, with a 25m grid spacing in both directions. The grid size was 100 x 60 cells. The water depth was 33.0 m, the weighted average of the depths at the two current meter deployments (ID246 and ID254, Table 2). The flowmetry file combined the data from ID246 and ID254 and comprised 93 days in duration in total.

Following the standard default approach, NewDepomod was used to simulate one year of deposition at the maximum farm biomass (2500 T and 3100 T). 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, 2019). The results are presented in Section 4.1.

3.2 Local Deposition: Hydrodynamic Model and Calibrated NewDepomod

The calibrated deposition modelling approach applied NewDepomod with realistic bathymetry and flow fields taken from a calibrated hydrodynamic model. NewDepomod was calibrated against the 2019 seabed survey data, producing a parameter set that predicted seabed impacts at the Creag an Sagairt site with an acceptable level of accuracy. The parameter set was then validated against the previous seabed survey data from 2013, 2015 and 2017. The calibration and validation process are described in more detail in the following sections. For the hydrodynamics, the RiCOM model (River and Coastal Ocean Model) was used, and four current datasets were used to calibrate and validate the model; the hydrodynamic modelling is described in a separate report submitted with this application.

3.2.1 NewDepomod Model Domain, Mesh and Bathymetry

When using NewDepomod with flow fields from hydrodynamic models, an unstructured mesh must be used. For the present application, the mesh covered an area of 2 km x 2 km around the site (Figure 3). The mesh consists of 2935 nodes and 5604 elements; the mean element area is 547 m^2. The regional bathymetry was taken from the UK Hydrographic Office (UKHO) data portal (https://seabed.admiralty.co.uk/).

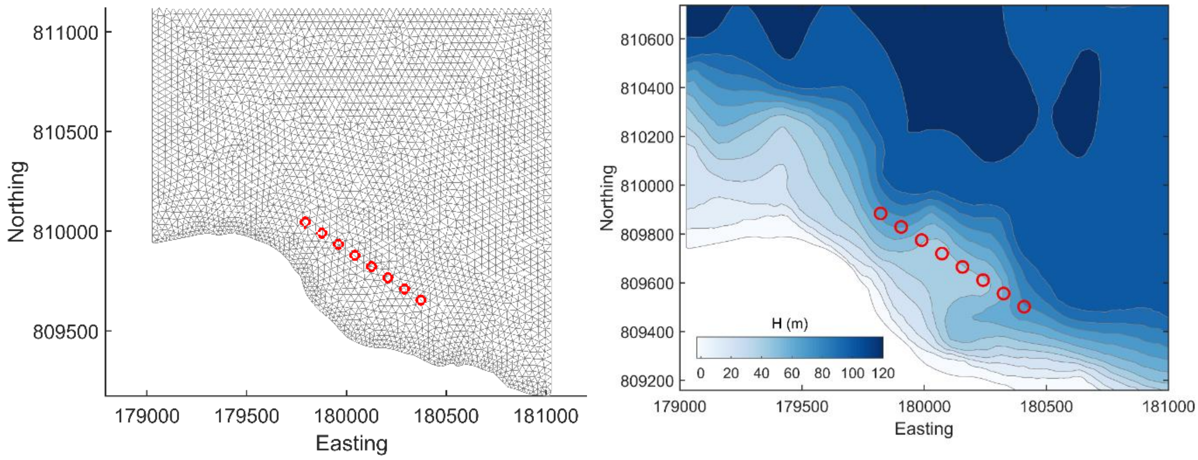

Figure 3. The unstructured mesh (left) and bathymetry (right) for the calibrated NewDepomod modelling. The locations of the proposed 160m cages are indicted (○).

3.2.2 NewDepomod Calibration

NewDepomod was calibrated against benthic survey data from December 2019 (Figure 2), and validated against three prior surveys in 2013, 2015 and 2017. The calibration process simulated the May 2018 – December 2019 production cycle, and established a relationship between the modelled deposition (in g m^{-2}) and measured IQI at all the sample locations (Figure 2). The simulation ran from the date of stocking to the date of the seabed surveys (567 days in total). The mean modelled deposition over the final 90 days of the simulation (i.e. days 477 – 567) was used to compare to the IQI data. By comparing the modelled deposition to the 35 values of IQI from the 2019 survey, a relationship between deposition and IQI was established, allowing the modelled deposition to be converted to an IQI score. In the present application, a logistic function was used to relate the modelled deposition to the observed IQI. From the modelled and observed IQI values, a root-mean-square error for the model results was calculated.

An acceptable relationship between modelled deposition and IQI was stipulated as occurring when the root-mean-square error (RMSE) of less than 0.1, which is 10% of the range of IQI values. Given that we are comparing a physical process (particulate deposition) with a biological response (IQI), some variability in the response is inevitable and an RMSE target of 0.1 seems challenging but reasonable and achievable.

The calibration process involved numerous simulations of the model with different parameter sets, seeking the parameter values that achieved the best comparison (smallest RMSE) with the IQI data. Over the course of the calibration process, the following NewDepomod parameters were varied over realistic ranges of values:

- Coefficients of horizontal and vertical diffusion (K_H, K_V)
- Seabed roughness, z_0
- The critical erosion stress threshold (tauECritMin)
- The mass of sediment per bed layer per grid cell (dLayerMass)
- The release height of resuspended particles (H_R)
- The half-lives of bed expansion and contraction
- The mass erosion coefficient
- The mass erosion exponent

Once a satisfactory relationship between the 90-day mean modelled deposition and IQI was established, the same parameter set was used in simulations of the 2012 – 2013, 2014 – 2015, and 2016 – 2017 production cycles, with the modelled 90-day mean deposition from each simulation tested against the three sets of IQI data from benthic surveys conducted in 2013, 2015 and 2017. Again, the full production cycle from stocking to seabed survey was modelled, and the mean deposition over the final 90 days of the simulation used in the model-data comparison. Cage layouts and feed inputs appropriate for each cycle were used (see §3.2.3). Scatter plots of modelled IQI versus predicted IQI are presented, and errors calculated. An RMSE ≤ 0.1 was again targeted for the validation simulations. Details of the calibration simulations are provided in Table 4.

Table 4. Details of the calibration simulations. The end of the simulations coincide with the start of the seabed survey for that cycle; the production cycle itself typically extends beyond the survey.

Run	Purpose	Start Date	End Date	Duration (days)	Consented Biomass (T)	Pen Layout
1	Calibration	26 May 2018	14 Dec 2019	567	2500	Cages-2016
2	Validation	16 Oct 2012	24 Nov 2013	404	3300	Cages-2012
3	Validation	18 Oct 2012	14 Dec 2015	1152	3300	Cages-2012
4	Validation	12 Aug 2016	05 Dec 2017	480	2500	Cages-2016

Note that although the consented biomass for each cycle is given in Table **4**, daily quantities of waste feed and faeces were calculated from the actual recorded daily feed rather than the nominal biomass.

Note also that the validation run to December 2015 (Run 3) started in October 2012, rather than in August 2014 when the production cycle started. The 2012-2014 production cycle had a relatively high daily feeding rate, and the effects of that feeding intensity were still affecting the benthic response in 2015, meaning that the simulation had to include inputs from 2012 – 2015 to accurately reproduce the effects.

3.2.3 NewDepomod Inputs

Inputs appropriate for each production cycle, including pen locations, daily feed input and hydrodynamic flow fields, were used in the calibration simulations. Two pen configurations, labelled 2012 and 2016, were used. Both consisted of 12 x 120m cages, but were grouped in different configurations (Figure 4). Details of the pens used in the simulations are provided in Table 5.

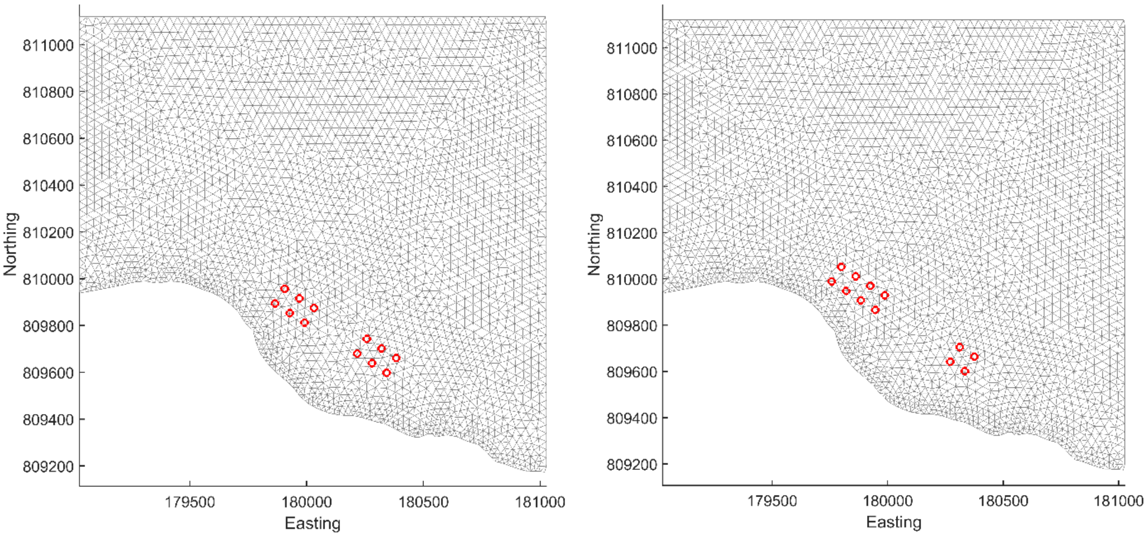

Figure 4. Pen layouts for the calibration simulations: cages2012 (left) used in the simulations between 2012 and 2015, and cages2016 (right) used in simulations from 2016 – 2019.

Table 5. Pen centre locations for the calibration simulations. All pens were 120m circumference, with a net depth of 16m.

	Cages2012		Cages2016	
Pen	Easting	Northing	Easting	Northing
1	179988	809929	179988	809929
2	179925	809970	179925	809970
3	179862	810011	179862	810011
4	179799	810052	179799	810052
5	179947	809866	179947	809866
6	179884	809907	179884	809907
7	179821	809948	179821	809948
8	179758	809989	179758	809989
9	180312	809705	180312	809705
10	180375	809664	180375	809664
11	180271	809642	180271	809642
12	180334	809601	180334	809601

Waste feed was estimated at 3% of the recorded daily feed input, and was distributed evenly between all 12 pens. Daily faeces input was calculated following SEPA (2019). The time series of inputs for the calibration simulation 2018 – 2019 are shown in Figure 5; time series for the validation simulations are shown in Figure 6.

3.2.4 Hydrodynamic Model Simulations and Coupling to NewDepomod

The hydrodynamic model was run for the final period of each NewDepomod simulation (Figure 5 and Figure 6). Running hydrodynamic models for whole NewDepomod simulations leads to very large flow files that NewDepomod cannot currently handle. The length of the hydrodynamic model simulations was typically in the range $80 < N < 120$ days, with the exact length of each hydrodynamic simulation, N days, being determined by the length of the NewDepomod simulation, such that $N = L/m$, with L being the length of the NewDepomod simulation (days) and m an integer. The purpose here is to ensure that the flow data is recycled an integer number of times during the NewDepomod simulation so that the correct flow data are applied for the final N days of the simulation leading up to the benthic survey date. The dates and durations of the hydrodynamic model simulations for each NewDepomod simulation are shown in Table 6.

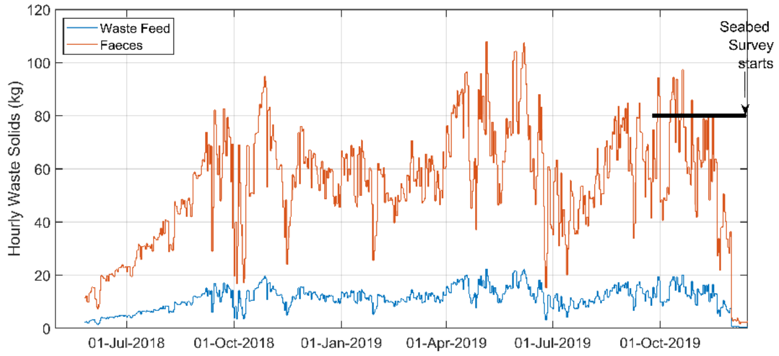

Figure 5. Time series of inputs, waste feed (blue) and faeces (red), for the calibration simulation from May 2018 – December 2019. The simulations run to the start of the seabed survey. The period covered by the hydrodynamic model simulation is indicted by the horizontal black line (▬).

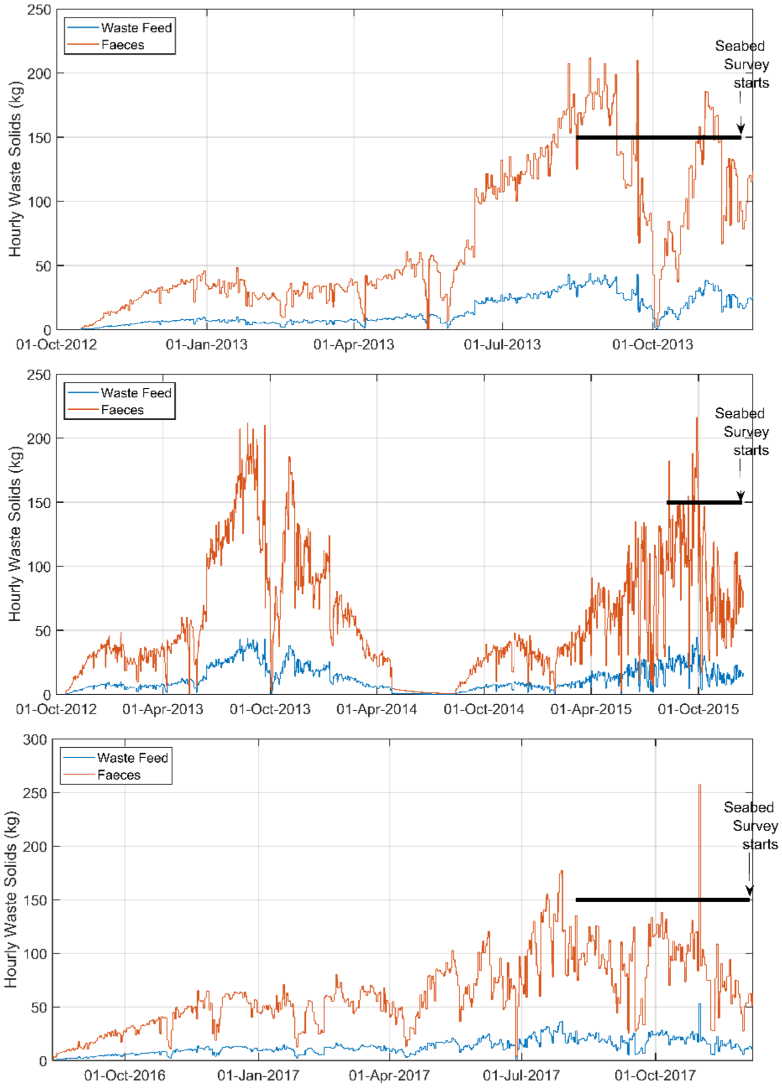

Figure 6. Time series of inputs, waste feed (blue) and faeces (red), for the validation simulations from October 2012 – November 2013 (top), October 2012 – December 2015 (middle) and August 2016 – December 2017 (bottom). The simulations run to the start of the seabed survey. The periods covered by the hydrodynamic model simulations are indicted by the horizontal black line (▬).

Table 6. Details of the hydrodynamic model simulations used for each NewDepomod calibration simulation. The number of cycles is the number of times the hydrodynamic model data file repeats during the NewDepomod simulation.

NewDepomod			Hydrodynamic Model			
Run	Purpose	Duration	Start	End	Duration (d)	No. Cycles
1	Calibration	567	24/09/2019	14/12/2019	81	7
2	Validation	404	15/08/2013	24/11/2013	101	4
3	Validation	1152	08/08/2015	14/12/2015	128	9
4	Validation	480	07/08/2017	05/12/2017	120	4

The velocity data from the hydrodynamic model were interpolated spatially onto the node locations of the NewDepomod mesh (Figure 3). The temporal resolution remains hourly in both cases, so temporal interpolation was not required. Modelled velocity flow fields were provided to NewDepomod at three sigma-depths: $\sigma = [0, -0.6, -0.95]$. A power law profile was applied to the depth-averaged model data in order to approximate a tidal velocity profile (Lewis et al., 2017), with factors of 1.14, 1.0 and 0.743 applied to the surface, middle and near-bed layers respectively. Velocity data at a fourth level, $\sigma = -1.0$, are also provided as standard, with $u = v = 0.0$.

3.2.5 Outputs

Files of predicted solids deposition across the model domain were output every 3 hours over the final 90 days of the NewDepomod simulations. During post-processing, the mean 90-day deposition at every grid cell was calculated. The mean deposition values at the sample locations from each survey (Figure 2, Table 3) were extracted and used to calibrate the model against the observed IQI data.

A relationship between modelled deposition and observed IQI was sought by fitting a logistic function to the results, such that:

$$\hat{y} = \frac{y_0}{(1 + e^{-\lambda(x' - x_0)})} \tag{1}$$

where $\hat{y}$ is the predicted IQI; λ, x_0 and y_0 are constants in the logistic function; and x' is the natural log of the mean modelled deposition x (g m^{-2}). The calibration process provided values of λ, x_0 and $y_{0,}$ which were then be used to convert the modelled deposition into predicted IQI.

3.2.6 Forecast of Proposed Development

For the proposed biomass of 3100 tonnes, NewDepomod was run with the parameter set developed by the calibration process, but using a constant feed load of 7 kg/tonne fish/day. The proposed pen layout is shown in Figure 3 and pen centre locations given in Table 7. The model was run for one year, with output files produced every 3 hours for the final 90 days. The mean deposition over the final 90 days was then calculated.

Table 7. Pen centre locations for the 8x160m pen forecast simulation. All pens were 160m circumference, with a net depth of 20 m.

Pen	Easting	Northing
1	180043	809879
2	179960	809935
3	179877	809991
4	179794	810046
5	180374	809655
6	180291	809711
7	180208	809767
8	180126	809823

3.3 Cumulative Deposition: Hydrodynamic Model and unptrack Deposition Model

The objective of the cumulative modelling is to assess potential interaction between deposition from Loch Hourn with deposits from neighbouring sites. Following the SEPA screening report (SEPA, 2021), the cumulative assessment will include seven sites in addition to the site at Loch Hourn (Table 8). For completeness, both active and currently inactive sites were included.

Since NewDepomod is not designed to simulate deposition from multiple sites spread over a wide area, the Mowi unptrack model (Gillibrand, 2021) was used to simulate the cumulative deposition. The unptrack model uses the same unstructured mesh as the hydrodynamic model, and reads the flow fields directly from the hydrodynamic model output files; therefore, no spatial or temporal interpolation of the current fields is required, although current velocities are interpolated to exact particle locations within unptrack.

Table 8. Sites to be included in the cumulative modelling assessment.

Site Name	Location	Operator	Consented Biomass (tonnes)	Status
HNW1	Loch Hourn	Mowi	3100 (proposed)	Active
ARDT1	Ardintoul	Mowi	2500	Active
ARNI1	Arnisdale	Mowi	125	Inactive
BEIS1	Loch na Beiste	Mowi	600	Inactive
CNG1	Camus nan Gall	Mowi	750	Inactive
DUI1	Duich	Mowi	2500	Active
EAR1	Earnsaig (Nevis A)	Scottish Sea Farms	1350	Active
SRO1	Sron	Mowi	2500	Active

3.3.1 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 continuously from pens during a production cycle. In addition to the pens at Creag an Sagairt, waste feed and faeces were released from the locations of the seven other sites (Table 9). Particles were discharged continuously, with each numerical particle representing 2.5 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.

When a particle reaches the seabed due to its settling velocities, it may be resuspended back into the water column and be subject again to advection and diffusion; alternatively, it may remained settled and be gradually consolidated into the seabed sediment. 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:

$$P = c_r(\tau_b - \tau_{bc})e^{(-t_p/\lambda)} \tag{2}$$

where $\tau_b = \rho u_*^2$ is the bed shear stress derived from the modelled near-bed velocity, τ_{bc} is the minimum critical shear stress required to erode particles off the seabed, c_r is a resuspension constant, t_p is the age of the particle and λ is a consolidation time scale. With this approach, the probability of particle resuspension decreases as the particle ages (scaled by λ) 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.

3.3.2 Deposition Model Calibration

Calibration of the unptrack model was performed by repeating the 2018 – 2019 production cycle simulation for Loch Hourn, as described above (§3.2.2), and finding a parameter set that produced acceptable agreement between the modelled mean deposition and the observed IQI values from December 2019. The calibration was performed by varying the horizontal and vertical diffusion coefficients, the bed roughness coefficient, and the constants in the resuspension equation. For this calibration, we used the same inputs as for NewDepomod (Figure 5) and the same hydrodynamic model simulation (Table 6).

Table 9. Locations of the additional seven sites included in the cumulative modelling.

Site	Easting	Northing
Arnisdale	184000	810280
Camas Nan Gall	188400	806700
Nevis A	174290	797360
Duich	189300	823100
Ardintoul	182180	824120
Sron	178360	825600
Loch na Beiste	175850	825400

Once a parameter set for unptrack had been selected, the model was run for one year for all sites. A constant feed rate of 7 kg/tonne of fish/day was used, with the proposed biomass at Loch Hourn and the consented biomass at the other seven sites applied (Table 8). The mean deposition over the final 90 days of the simulation was calculated.

3.4 In-Feed Treatment (Slice) Modelling

Deposition of Slice will be modelled using both the standard default method and the calibrated model. The simulations were optimised, to find the quantity of emamectin benzoate that can be discharged and meet the SEPA interim EQS of 23.5 ng kg^{-1} dry weight i.e. 11.75 ng kg^{-1} wet weight. The model was run in standard fashion, with treatment taking place over 7 days, and the mean deposition after 116 – 118 days post-treatment calculated.

4. RESULTS

4.1 NewDepomod: SEPA Standard Default Method

4.1.1 Current Biomass: 2500 tonnes

The modelled footprint for the existing farm using the SEPA standard default method is shown in Figure 7. The area of the footprint, as defined by the deposition rate of 250 g m^{-2}, was 283,750 m^2, which is 30% bigger than the allowable mixing zone (Table 10). However, the measured ellipse area in December 2019 was 182,217 m^2, 16% less than the allowable mixing zone. It should be noted that the SEPA standard default method is designed as a risk assessment tool and is not expected to accurately map the deposition footprint; the use of single-point current data and flat bathymetry preclude this. The comparison between modelled deposition and observed IQI for Loch Hourn (Figure 7), and the excessive modelled footprint area, demonstrate that the standard default method does not work particularly well for this site, at least in terms of predicting the footprint area. The mean intensity of deposition within the footprint was 1956.5 g m^{-2}.

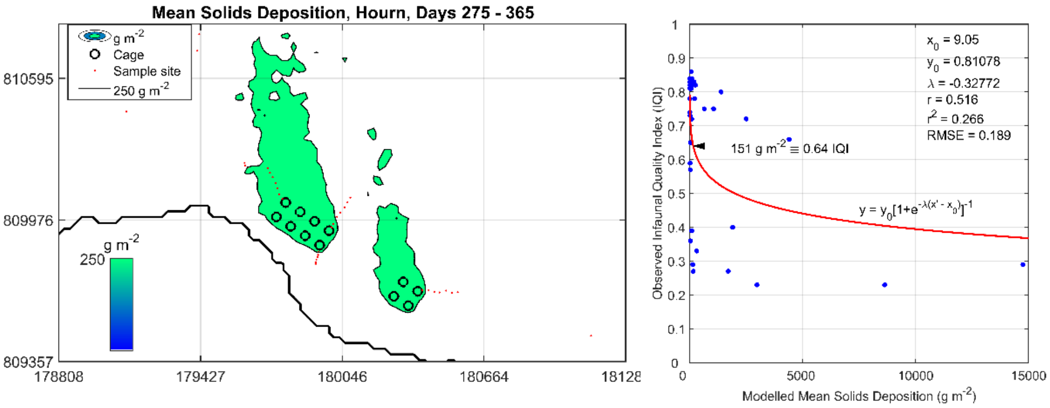

Figure 7. The modelled footprint for Loch Hourn (right) for the current consented biomass of 2500 tonnes, using the SEPA standard default method. The area shaded green indicates the area with a deposition greater than 250 g m^{-2}, thought to equate approximately with an IQI of 0.64. The 35 seabed sample locations from December 2019 are indicated in red (○). The comparison between modelled mean deposition and the measured IQI at the sample locations is shown on the right.

Table 10. The modelled footprint areas for Loch Hourn for the current and historic biomasses, using the SEPA standard default method, compared against the allowable mixing zone and the observed ellipse area from December 2019.

	Current	**Historic**
Consented Biomass (T)	2500	3300
Feed load (T/yr)	6387.5	8431.5
Solid Waste release rate (kg/day)	2794.8	3689.1
Allowable Mixing Zone (m^2)	217,341	217,341
Observed Ellipse Area (m^2)	182,217	-
Modelled Footprint (m^2)	283,750	430,000
Mean Footprint Deposition (g m^{-2})	1956.5	2047.0

4.1.2 Historical Biomass: 3300 tonnes

We also modelled the footprint for the historical farm biomass of 3300 T using the SEPA standard default method (Figure 8) The area of the footprint, as defined by the deposition rate of 250 g m^{-2}, was 430,000 m^2, which is almost double the allowable mixing zone (Table 10).

The mean intensity of deposition within the footprint for 3300 tonnes was 2047 g m^{-2} (Table 10). It is of interest to note that the site failed the pen edge standard in 2013 with this higher predicted mean footprint deposition, although it has passed that standard on each survey since when the predicted footprint intensity was lower. The standard default method appears to predict the effects of the intensity of deposition on pen edge compliance at this site better than the footprint area. The compliance history of the site is described in Section 10.5.4 in the accompanying Environmental Impact Assessment.

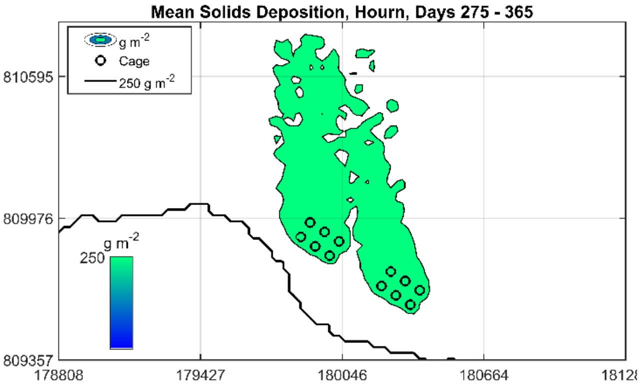

Figure 8. The modelled footprint for Loch Hourn (right), for the historical biomass of 3300 tonnes, using the SEPA standard default method. The area shaded green indicates the area with a deposition greater than 250 g m^{-2}, thought to equate approximately with an IQI of 0.64.

4.1.3 Proposed Biomass: 3100 tonnes

The modelled footprint for the proposed farm using the SEPA standard default method is shown in Figure 9. The area of the footprint, as defined by the deposition rate of 250 g m^{-2}, was 470,000 m^2, which is more than double the allowable mixing zone (Table 10). However, we have seen that the standard default method does not work well for the Creag an Sagairt site, in terms of predicting the footprint area. In the following section, we develop a calibrated application of NewDepomod which more accurately predicts the seabed impact across four production cycles at this site.

The modelled mean intensity of deposition within the footprint for the proposed biomass was 1698.7 g m^{-2} (Table 11), less than current and historical values (Table 10), perhaps reflecting the reduced stocking density with the proposed pen configuration.

Table 11. The modelled footprint areas for Loch Hourn for the current and proposed biomasses, using the SEPA standard default method, compared against the allowable mixing zone for the existing and proposed cage layouts and the observed ellipse area from December 2019.

	Proposed
Consented Biomass (T)	3100
Feed load (T/yr)	7920.5
Solid Waste release rate (kg/day)	3465.5
Allowable Mixing Zone (m^2)	220,218
Modelled Footprint (m^2)	470,000
Mean Footprint Deposition ($g\ m^{-2}$)	1689.7

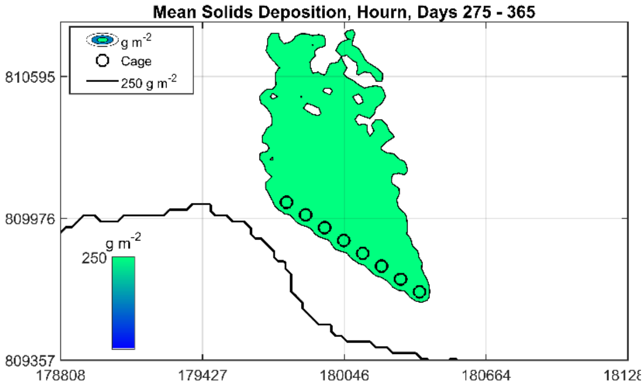

Figure 9. The modelled footprint for Loch Hourn (right), for the proposed biomass of 3100 tonnes, using the SEPA standard default method. The area shaded green indicates the area with a deposition greater than 250 g m^{-2}, thought to equate approximately with an IQI of 0.64.

4.2 NewDepomod: Calibrated Modelling

4.2.1 Hydrodynamic Model Currents

The calibration and validation of the hydrodynamic model for Loch Hourn against four current meter data records is described in the accompanying report. The hydrodynamic model used for the calibrated NewDepomod simulations used the same model configuration, but was run for the periods appropriate for the NewDepomod simulations (Table 6, Figure 5, Figure 6). Scatter plots of modelled velocity at the central location of the proposed cages (180023E 809857N) for the four simulation periods are shown in Figure 10.

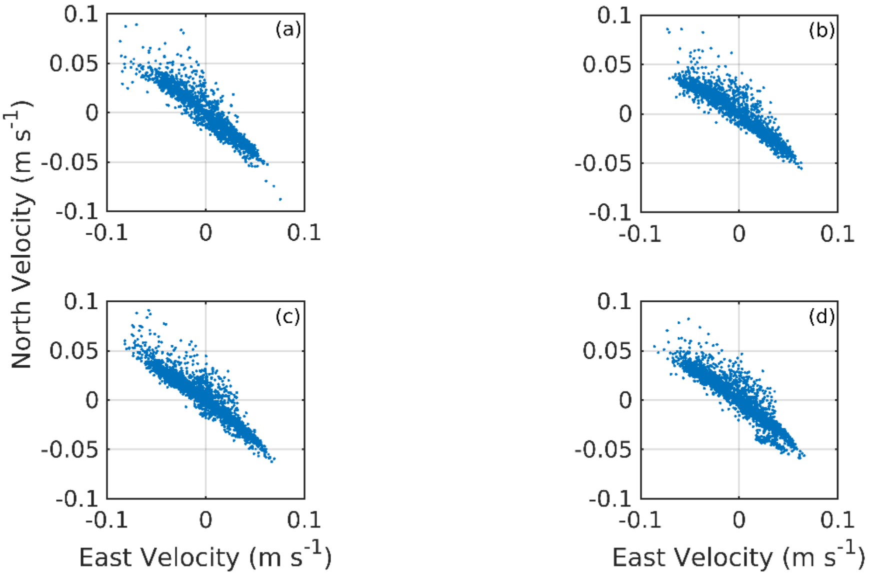

Figure 10. Scatter plots of the modelled East and North velocity at the centre of the proposed farm site (180023E 809857N) for the four simulation periods list in Table 6: (a) 24 Sept 2019 – 14 Dec 2019; (b) 15 Aug 2013 – 24 Nov 2013; (c) 08 Aug 2015 – 14 Dec 2015; (d) 07 Aug 2017 – 05 Dec 2017.

The different simulations exhibited consistent tidal currents at the location, with minor variations due to the prevailing wind and river flow conditions.

4.2.2 NewDepomod Calibration

The calibration simulation ran from 26th May 2018 – 14 December 2019 (Table 4). After multiple simulations of this production cycle, a parameter set was selected for all further calibrated model simulations (Table 12).

Table 12. Parameter values for the key model parameters for the calibrated NewDepomod simulations. All other model parameters used the same values as the SEPA standard default method.

Parameter	Value
Horizontal diffusion coefficient, K_X, K_Y (m^2 s^{-1})	0.1
Vertical diffusion coefficient, K_Z (m^2 s^{-1})	0.001
Seabed roughness lengthscale, z_0 (m)	0.01
Critical erosion stress threshold, τ_{bc} (Pa)	0.02
Particle resuspension release height (m)	0.35
Mass of sediment per bed layer per grid cell (kg)	48.8907
Release position of resuspended particles	RANDOM
Walker type	UNIFORM
Bed expansion half-life (s)	604800
Bed contraction half-life (s)	900

The output from the model was the mean deposition from the final 90 days of the simulation i.e. from 15th September 2019 – 14th December 2019. The modelled mean deposition using the parameter set in Table 12 is shown in Figure 11. The distribution illustrates the effect of using spatially-varying flow fields from a hydrodynamic model on variable bathymetry. The comparison between modelled deposition and observed IQI from December 2019 is much improved from the standard default model, with an RMSE of 0.082, meeting the target of < 0.1.

Fitting a logistic function to the data resulted in an IQI predictor, $\hat{y}$, given by:

$$\hat{y} = \frac{0.82063}{(1+ e^{0.92505(x'-7.7645)})} \qquad (3)$$

where x is the modelled 90-day mean deposition. The calibration, in this particular case, equates a deposition of 600 g m^{-2} with an IQI of 0.64 (Figure 11).

Applying the predictor equation (3) to the modelled deposition enables the calculation of the predicted IQI (Figure 12) and allows the modelled footprint area to be calculated (Table 13): a value of 177,790 m^2 was obtained, within 3% of the measured ellipse area in December 2019. Using spatially-varying currents, realistic bathymetry, real feed inputs, and modifying the NewDepomod parameter set all help to improve the accuracy of model predictions.

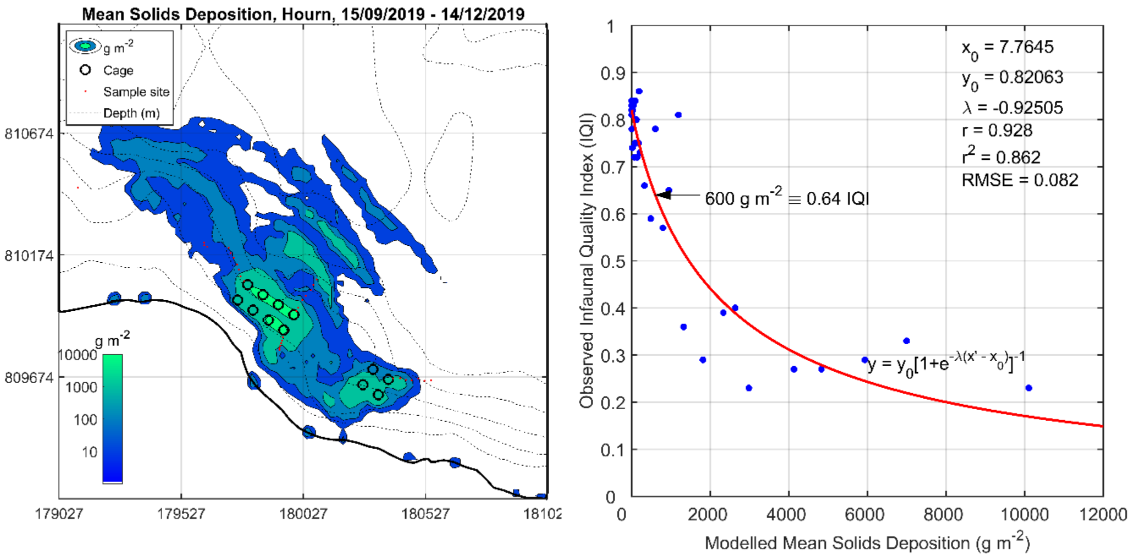

Figure 11. Results of the calibration for May 2018 – December 2019. The 90-day mean deposition is shown (left), with the sample locations from December 2019 also indicated (○). On the right, the relationship between the modelled deposition and the observed IQI at the sample locations is shown. The logistic function (▬) relating deposition with IQI is used to forecast the future footprint. Values of the correlation coefficient (r) and root-mean-square error (RMSE) are shown.

Once the calibration parameter set (Table 12) was established, it was tested against seabed data from previous production cycles (validation Runs 2 – 4, Table 4). Fewer samples were collected in these older surveys. The results for 2012 – 2013 (Figure 13), 2012 – 2015 (Figure 14) and 2016 – 2017 (Figure 15) are presented below. The RMSE values for two of these simulations were below 0.1 (Table 13); the RMSE for the 2015 survey was very slightly above 0.1. The small number of data samples for each of these older surveys makes the calculated errors less robust. Overall, the agreement between modelled and observed IQI is very good, demonstrating that with careful configuration and calibration, NewDepomod is able to predict seabed impacts from waste solids with a reasonable degree of accuracy.

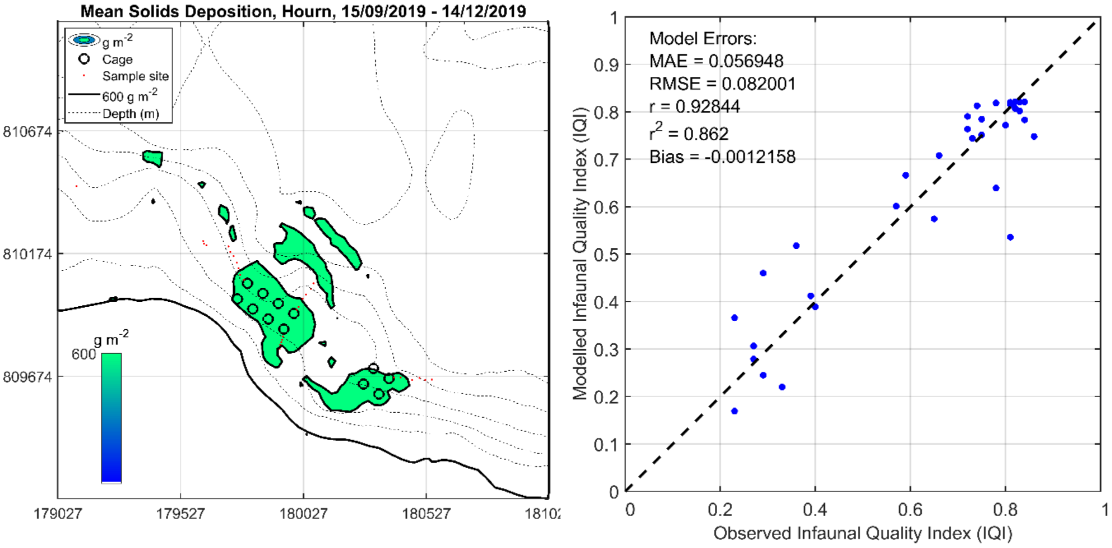

Figure 12. Results of the calibration for May 2018 – December 2019. The 600 g m^{-2} contour of the 90-day mean deposition is plotted (left), defining the modelled footprint area where the predicted IQI < 0.64. The sample locations from December 2019 are indicated (○). On the right, the predicted IQI at the sample locations is plotted against the observed IQI.

Table 13. Results from the calibration simulations. The Run numbers refer to Table 4.

	Run 1 2018 – 2019	Run 2 2012 – 2013	Run 3 2012 – 2015	Run 4 2016 – 2017
Allowable Mixing Zone (m^2)	217,341	217,341	217,341	217,341
Observed Ellipse Area (m^2)	182,217	-	-	-
Modelled Footprint (m^2)	177,790	169,680	223,329	175,294
RMSE	0.082	0.075	0.108	0.089

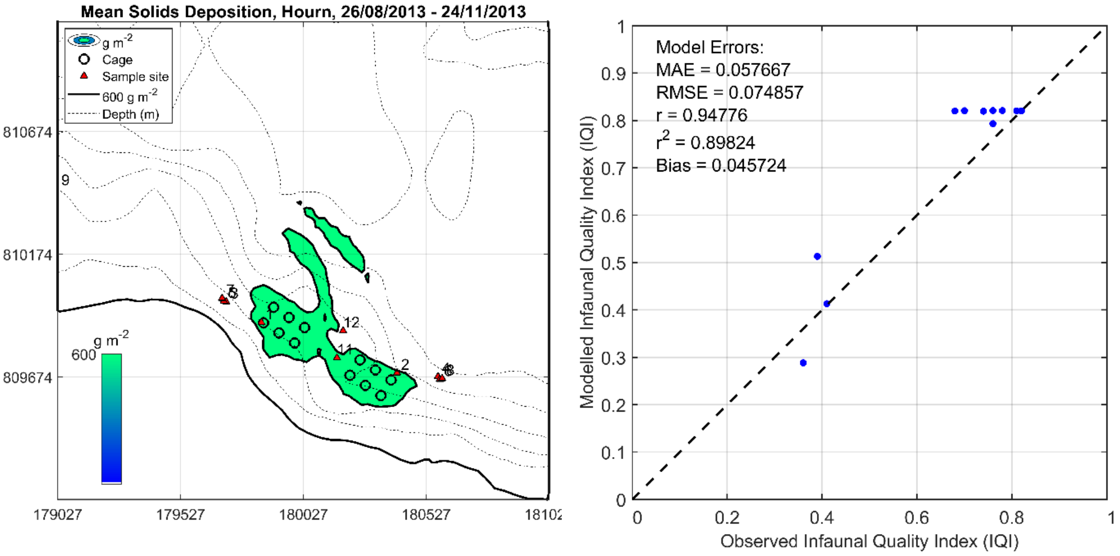

Figure 13. Results of the validation for October 2012 – November 2013. The 600 g m^{-2} contour of the 90-day mean deposition is plotted (left), defining the modelled footprint area where the predicted IQI < 0.64. The sample locations from November 2013 are indicated (▲). On the right, the predicted IQI at the sample locations is plotted against the observed IQI.

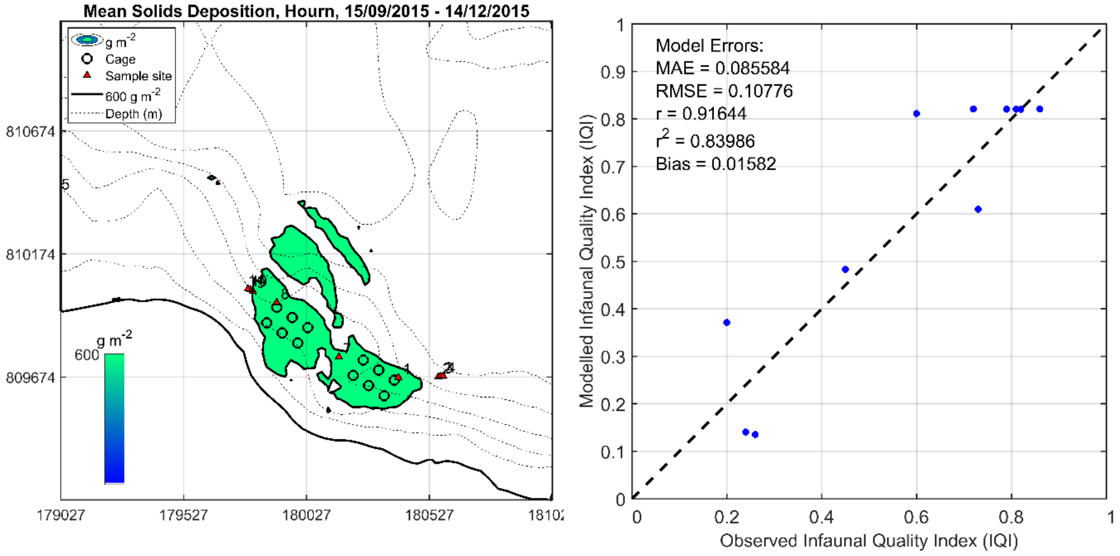

Figure 14. Results of the validation for October 2012 – December 2015. The 600 g m^{-2} contour of the 90-day mean deposition is plotted (left), defining the modelled footprint area where the predicted IQI < 0.64. The sample locations from December 2015 are indicated (▲). On the right, the predicted IQI at the sample locations is plotted against the observed IQI.

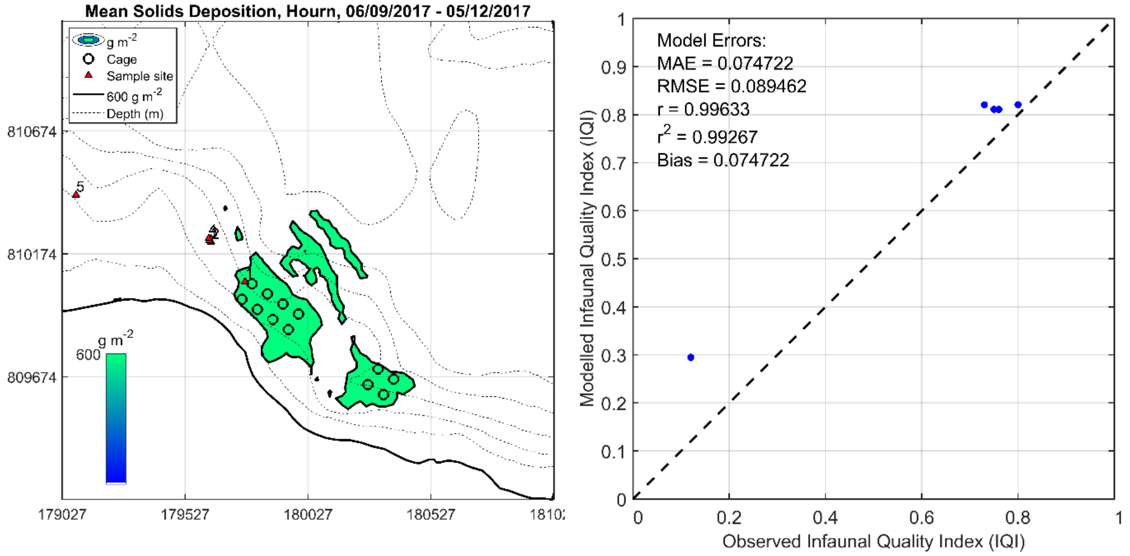

Figure 15. Results of the validation for August 2016 – December 2017. The 600 g m^{-2} contour of the 90-day mean deposition is plotted (left), defining the modelled footprint area where the predicted IQI < 0.64. The sample locations from December 2017 are indicated (▲). On the right, the predicted IQI at the sample locations is plotted against the observed IQI.

The ultimate objective of the NewDepomod simulations is to be able to predict where the seabed is impacted by waste solids such that the IQI falls below 0.64. Over the four NewDepomod simulations, 19 (90%) of the 21 samples where the IQI < 0.64 were correctly predicted by the model (Table 14). Similarly, 40 (93%) of the 43 samples where the observed IQI 0.64 were correctly predicted. The Probability of Detection (POD) is therefore 92% (59 out of 64 samples). The Hit Rate, the correct prediction of an IQI < 0.64, is 90% (19 out of 21 samples), and the number of False Positives (predicted IQI > 0.64 when the observed IQI <

0.64) was 9.5% (2 out of 21 samples). Overall, then, the calibrated model had a success rate of over 90% in terms of overall prediction (POD) and predicting IQI values < 0.64 (Hit Rate). Given the complexity of the modelled processes, and the inherent uncertainty in the biological response to organic waste deposition, we believe this is a strong result.

Table 14. Numbers of collected samples from compliance surveys from 2013 – 2019 with an IQI les than or greater than 0.64 and the number of corresponding modelled values that correctly predict each case.

	Observed		**Total**
Predicted	**IQI < 0.64**	**IQI > 0.64**	
< 0.64	19	3	22
> 0.64	2	40	42
Total	21	43	64

The intensity of deposition for each simulation are summarised in Table 15. The "mean footprint deposition" is the 90-day mean deposition averaged over the area within the 600 g m^{-2} contour level. Values are typically about 3500 g m^{-2}, except for the longer 2012 – 2015 simulation which has a mean intensity of over 7000 g m^{-2}. This high value highlights the lack of simulated decay of organic material or sediment re-working within NewDepomod.

Table 15. Results from the calibrated model run for the proposed biomass of 3100 tonnes in 8 x 160m pens.

	Run 1 2018 – 2019	Run 2 2012 – 2013	Run 3 2012 – 2015	Run 4 2016 – 2017
Consented Biomass (tonnes)	2500	3300	3300	2500
Nominal stocking density (kg m^{-3})	11.36	15.00	15.00	11.36
Total feed load (tonnes)	5569.6	5339.2	12094.1	5466.3
Total solids released (tonnes)	889.5	852.7	1931.5	873.0
Mean solids released (kg day^{-1})	1568.8	2110.6	1676.6	1818.8
Mean footprint deposition (g m^{-2})	3491.2	3789.2	7359.8	3538.7

4.2.3 Proposed Biomass: 3100 tonnes

NewDepomod was run with the calibrated parameter set for the proposed biomass of 3100 tonnes in a pen configuration of 8 x 160m. The model was run with a standard feed load of 7 kg/tonne fish/day for one year, with the modelled mean deposition taken from the final 90 days of the simulation. The calibrated footprint is shown in Figure 16 and the results shown in Table 16.

The results indicate that the predicted footprint will comfortably meet the allowable mixing zone. The mean predicted footprint deposition of 5560.7 g m^{-2} falls within the range of the historical predictions (Table 15). **However, it should be noted that the standard calculation of feed load (7 kg/tonne/day) used in the forecasting produces a rate of waste solids deposition (3465.5 kg day^{-1}, Table 16) that is extremely high compared to actual historical rates at the site (Table 15), even allowing for the proposed increase in biomass.**

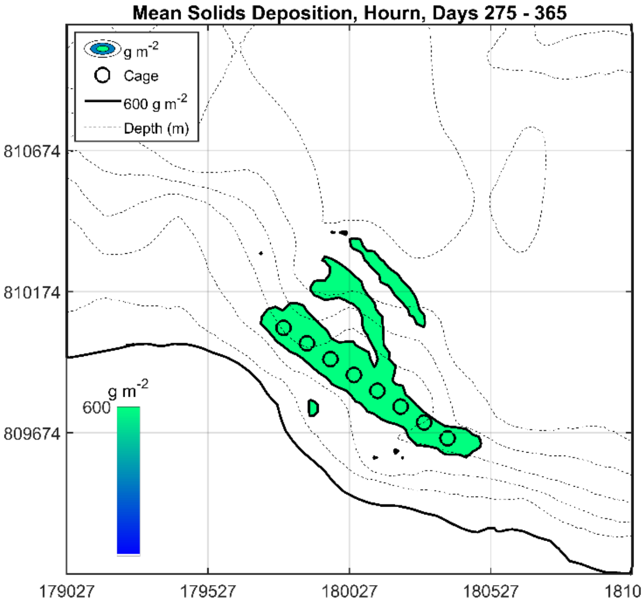

Figure 16. The modelled footprint for Loch Hourn (right), for the proposed biomass of 3100 tonnes, using the calibrated NewDepomod method. The area shaded green indicates the area with a deposition greater than 600 g m^{-2}, which has been shown to equate to an IQI of 0.64.

Table 16. Results from the calibrated model run for the proposed biomass of 3100 tonnes in 8 x 160m pens.

	Calibrated Model
Biomass (tonnes)	3100
Stocking density (kg m^{-3})	9.51
Total feed load (tonnes yr^{-1})	7920.5
Total solids released (tonnes)	1264.9
Total solids released (kg day^{-1})	3465.5
Allowable mixing zone (m^2)	220,218
Predicted footprint area (m^2)	175,918
Mean footprint deposition (g m^{-2})	5560.7

4.3 Cumulative Deposition

4.3.1 unptrack Calibration

The regional deposition model, unptrack, was calibrated by repeating the 2018 – 2019 production cycle as described above, using real feed inputs, realistic bathymetry and the same flow fields used by NewDepomod. As with NewDepomod, the wastes were distributed evenly between the 12 pens. Only the Creag an Sagairt site was included in the initial calibration simulation. The free parameters in the deposition model were selected to produce the best comparison with the seabed data from December 2019 (Table 17). The mean deposition over the final 90 days of the simulation was calculated for comparison with the IQI data.

Table 17. Values for the key model parameters for the unptrack cumulative deposition simulations.

Parameter	Value
Horizontal diffusion coefficient, K_X, K_Y (m^2 s^{-1})	0.1
Vertical diffusion coefficient, K_Z (m^2 s^{-1})	0.001
Seabed roughness length scale, z_0 (m)	0.01
Critical erosion stress threshold, τ_{bc} (Pa)	0.02
Particle resuspension release height (m)	0.35
Resuspension constant, c_r	10.0
Consolidation time scale, λ (days)	4.0

The resulting modelled mean solids deposition, and the comparison with the measured IQI data, are shown in Figure 17. The model produces a reasonable prediction of the IQI data (RMSE = 0.10), particularly given its relative simplicity compared to NewDepomod.

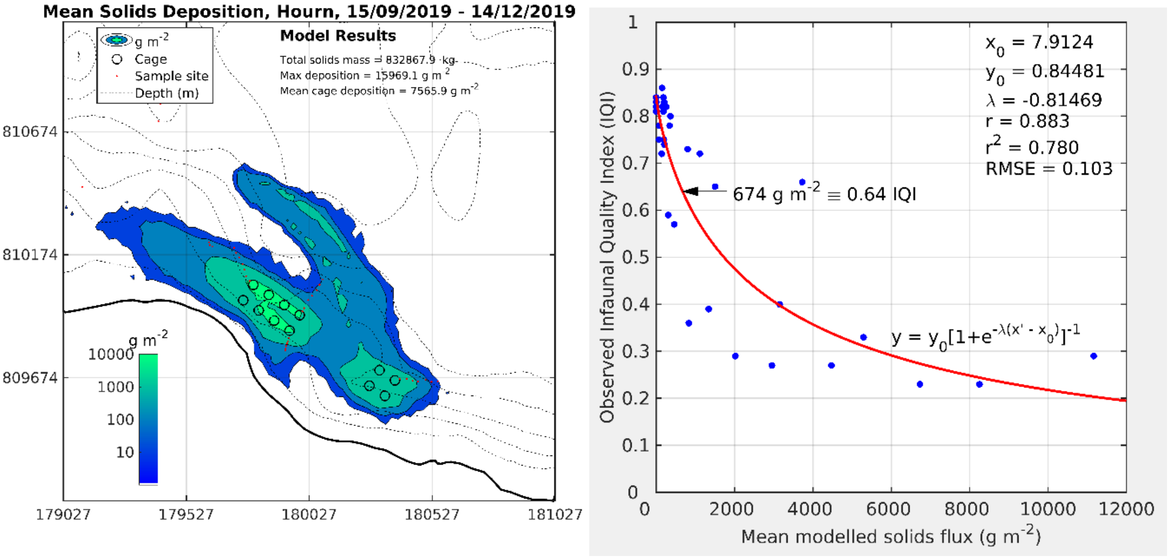

Figure 17. Calibration of the unptrack deposition model. The predicted mean 90-day deposition from September – December 2019 is shown on the left. The sample locations are indicated (○). The relationship between modelled mean deposition and observed IQI at the 35 sample locations is shown on the right. The red curve indicates the logistic function fit to the data.

4.3.2 Predicted Deposition from All Sites

The predicted deposition from the consented biomass (Table 8) at neighbouring sites is shown in Figure 18. The solids waste discharged from Loch Hourn does not appear to interact with that from any other site, which is confirmed by plotting the results from Loch Hourn only (Figure 19).

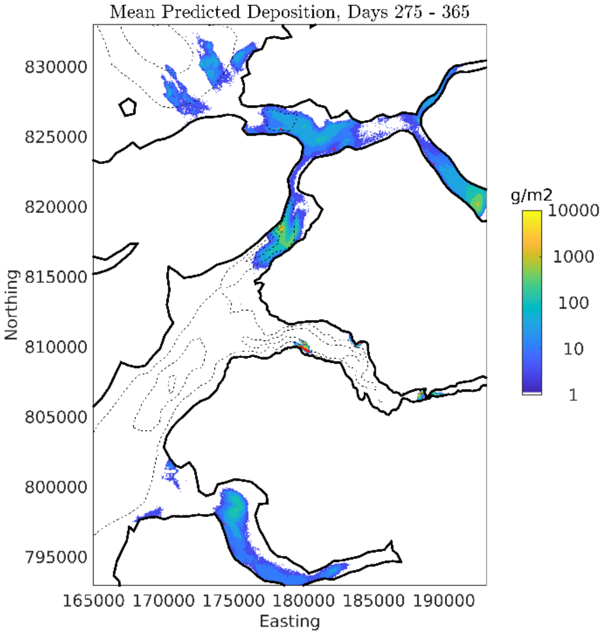

Figure 18. Modelled mean deposition from Loch Hourn and neighbouring sites at proposed and consented biomasses (Table 8) using the unptrack model.

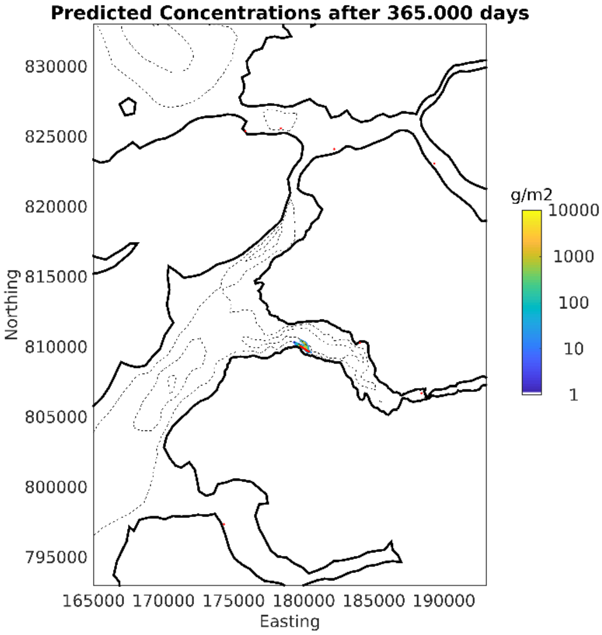

Figure 19. Modelled mean deposition from Loch Hourn only for the proposed biomass of 3100 tonnes using the unptrack model (Table 8).

4.4 In-Feed Treatments (Slice)

Optimised results of the deposition of emamectin benzoate following treatment using both the standard default method and the calibrated model are presented below.

4.4.1 Standard Default Method

The standard default method achieved compliance with the interim EQS with a discharged mass of emamectin benzoate of 2.1 g (Figure **20**, Table 18), enough to treat a biomass of 6.1 tonnes.

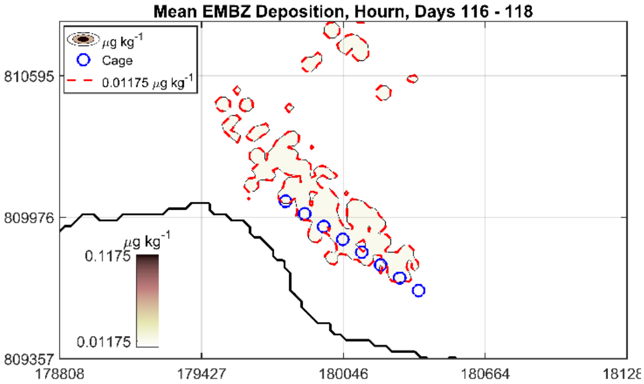

Figure 20. Predicted mean EmBZ concentrations after 116 – 118 days using the SEPA standard default method. The total mass of emamectin benzoate discharged was 2.1 g.

Table 18. Results from the optimised modelling of the in-feed treatment medicine emamectin benzoate.

	Standard Default	**Calibrated Model**
Biomass of fish (tonnes)	6.1	5.5
Over-Treatment Factor	1.0	1.0
Mass of EmBZ released (g)	2.1	1.9
Mass of EmBZ exported (g)	0	0
Far-Field Area Limit (m^2)	220,218	220,218
Area > 11.75 ng kg^{-1} (m^2)	167,500	213,348
Area > 117.5 µg kg^{-1} (m^2)	0	9,981
Peak concentration (ng kg^{-1})	91	342

4.4.2 Calibrated Model

The calibrated model achieved compliance with the interim EQS with a discharged mass of emamectin benzoate of 1.9 g (Figure 21, Table 18), enough to treat a biomass of 5.5 tonnes.

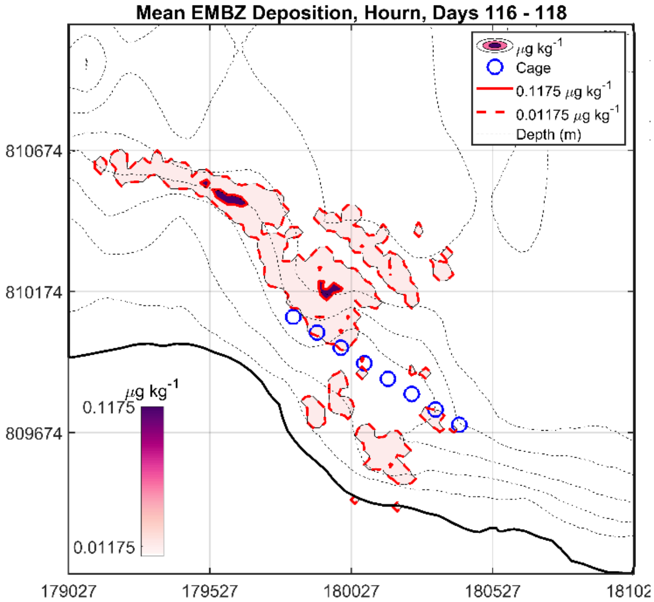

Figure 21. Predicted mean EmBZ concentrations after 116 – 118 days using the calibrated model. The total mass of emamectin benzoate discharged was 1.9 g.

5. SUMMARY AND CONCLUSIONS

The biomass and treatment amounts requested for consent at this site are given below (Table 19). The calibrated model indicates that the proposed biomass will not breach the allowable mixing zone area. The SEPA standard default method, which appears to predict the intensity of deposition better than the footprint area for this site, indicates that the lower stocking density proposed in this application will improve the pen edge deposition rates.

Table 19. Summary of Modelling Results.

SITE DETAILS			
Site Name:		Creag an Sagairt	
Site location:		Loch Hourn	
Peak biomass (T):		3,100	
Proposed feed load (T/yr):		7920.5	
CAGE DETAILS			
Number of cages:		8	
Cage dimensions:		160m Circumference	
Working Depth (m):		20	
Cage group configuration:		1 x 8, 100m matrix	
HYDROGRAPHIC SUMMARY			
		ID246	**ID254**
Surface Currents	Average Speed (m/s)	0.066	0.043
	Residual Direction (°G)	330	326
	Wind-Influence	Strong	Strong
Middle Currents	Average Speed (m/s)	0.053	0.039
	Residual Direction (°G)	335	307
Seabed Currents	Average Speed (m/s)	0.037	0.042
	Residual Direction (°G)	341	354
BENTHIC MODELLING			
Max fish biomass proposed (T)		3,100t	
Max Average Stocking Density (kg/m³)		9.51	
IN-FEED TREATMENTS			
Recommended consent mass EmBZ (g)		2.1	
Equivalent Fish Biomass (T)		6.1	
Maximum Treatment Amount EmBZ (g)		2.1	

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Lewis, M., Neill, S.P., Robins, P., Hashemi, M.R., Ward, S., 2017. Characteristics of the velocity profile at tidal-stream energy sites. Renewable Energy, 114, 258-272.

SEPA, 2019. Regulatory modelling guidance for the aquaculture sector. Air & Marine Modelling Unit, Scottish Environment Protection Agency, July 2019, 75 pp.

ANNEX A

Table A.1. Observed and predicted values of the Infaunal Quality Index (IQI) on the four seabed surveys of Loch Hourn in 2013, 2015, 2017 and 2019.

Station	Day	Month	Year	Observed IQI	Predicted IQI
1	24	11	2013	0.36	0.29
2	24	11	2013	0.41	0.41
3	24	11	2013	0.81	0.82
4	24	11	2013	0.74	0.82
5	24	11	2013	0.82	0.82
6	24	11	2013	0.68	0.82
7	24	11	2013	0.81	0.82
8	24	11	2013	0.70	0.82
9	24	11	2013	0.78	0.82
10	24	11	2013	0.76	0.82
11	24	11	2013	0.39	0.51
12	24	11	2013	0.76	0.79
1	14	12	2015	0.26	0.14
2	14	12	2015	0.82	0.82
3	14	12	2015	0.81	0.82
4	14	12	2015	0.79	0.82
5	14	12	2015	0.86	0.82
6	14	12	2015	0.72	0.82
7	14	12	2015	0.20	0.37
8	14	12	2015	0.24	0.14
9	15	12	2015	0.45	0.48
10	15	12	2015	0.73	0.61
11	15	12	2015	0.60	0.81
1	4	12	2017	0.12	0.29
2	4	12	2017	0.75	0.81
3	4	12	2017	0.76	0.81
4	4	12	2017	0.76	0.81
5	4	12	2017	0.73	0.82
6	4	12	2017	0.80	0.82
1	15	12	2019	0.29	0.24
2	15	12	2019	0.82	0.81
3	15	12	2019	0.83	0.80
4	15	12	2019	0.82	0.81
5	15	12	2019	0.84	0.82
6	15	12	2019	0.83	0.82
7	16	12	2019	0.23	0.37
8	16	12	2019	0.66	0.71
9	16	12	2019	0.72	0.76
10	16	12	2019	0.80	0.77
11	16	12	2019	0.75	0.78
12	16	12	2019	0.75	0.75
13	15	12	2019	0.23	0.17
14	15	12	2019	0.27	0.28
15	15	12	2019	0.78	0.64
16	15	12	2019	0.72	0.79
17	15	12	2019	0.84	0.78
18	15	12	2019	0.86	0.75
19	15	12	2019	0.81	0.54
20	14	12	2019	0.40	0.39

21	15	12	2019	0.29	0.46
22	14	12	2019	0.65	0.57
23	15	12	2019	0.73	0.74
24	14	12	2019	0.74	0.81
25	15	12	2019	0.78	0.82
26	15	12	2019	0.81	0.82
27	15	12	2019	0.33	0.22
28	15	12	2019	0.27	0.31
29	15	12	2019	0.39	0.41
30	15	12	2019	0.36	0.52
31	15	12	2019	0.57	0.60
32	15	12	2019	0.59	0.67
33	15	12	2019	0.81	0.82
34	15	12	2019	0.82	0.82
35	15	12	2019	0.84	0.82