Ardgour (Linnhe), CAR/L/1009970
Waste Solids Deposition Modelling Report

Mowi Scotland Ltd.

March 2023

Mowi Scotland	OFFICE Mowi, Farms Office, Glen Nevis Business Park PH33 6RX Fort William	[redacted]
	POSTAL Mowi, Farms Office, Glen Nevis Business Park PH33 6RX Fort William	

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EXECUTIVE SUMMARY

Mowi seeks a temporary increase to the maximum biomass consented at the Ardgour fish farm for a period of four months in 2023. Model simulations have been performed to assess the potential deposition of waste solids at the Ardgour (Linnhe) salmon farm in Loch Linnhe as a result of this temporary biomass increase. This report explains the application of the NewDepomod model to describe the deposition of waste solids 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 Ardgour together with deposition from nearby site at Gorsten is also presented using a coupled hydrodynamic model with Mowi's in-house particle tracking model UnPTRACK (Gillibrand, 2021).

Results indicated that the difference in deposition at Ardgour between the existing and temporary proposed biomass consents will be relatively low, with a very slight increase in footprint size using the SEPA standard default method with NewDepomod (Table 1). This method is known to be conservative.

Cumulative modelling indicated that the deposited wastes from Ardgour will not interact with solid wastes discharged from the neighbouring site at Gorsten.

Table 1. Site details & summary of results

Site Details	
Site Name:	Ardgour (Linnhe)
Site Location:	Ardgour
Peak Biomass (T):	3,000
Feed Load (T/year):	7,665
Pen Details	
Number of Pens:	10
Pen Dimensions:	120m Circumference
Working Depth (m):	16
Configuration:	2x5, 75m matrix
NewDepomod Results	
Allowable Mixing Zone (m^2):	154,887
Maximum Deposition ($g\ m^{-2}$):	13,258.9
Modelled Footprint (m^2):	790,625
Mean Footprint Deposition ($g\ m^{-2}$):	978.7
WeStCOMS2-UnPTRACK Results	
Allowable Mixing Zone (m^2):	154,887
Maximum Deposition ($g\ m^{-2}$):	13,258.9
Modelled Footprint (m^2):	192,500
Mean Footprint Deposition ($g\ m^{-2}$):	5255.0

1 INTRODUCTION

This report has been prepared by Mowi Scotland Ltd. to describe the deposition of waste solids from the marine salmon farm Ardgour (Linnhe; Figure 1 and Figure 2). Mowi seeks a temporary increase to the maximum biomass consented at the Ardgour fish farm in 2023, to allow the current generation of fish to be held on site for an extra four months. Model simulations have been performed to assess the potential deposition of waste solids at the Ardgour (Linnhe) salmon farm in Loch Linnhe as a result of this temporary biomass increase. The report describes the application of the NewDepomod model to simulate the deposition of waste solids 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 Ardgour together with deposition from the nearby site at Gorsten is also presented using a coupled hydrodynamic model with Mowi's in-house particle tracking model UnPTRACK (Gillibrand, 2021).

Figure 1. Location of the Ardgour Site

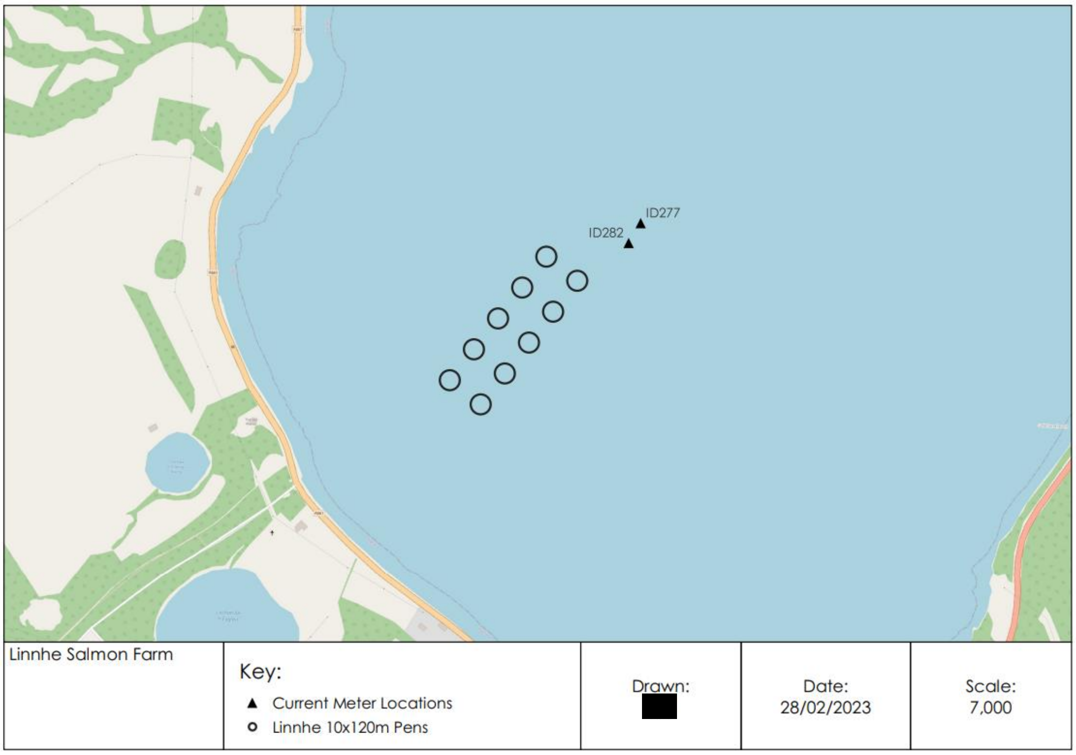

Figure 2. Existing layout at the Ardgour salmon farm. ADCP deployment locations are also marked with a black triangle

Table 2. Summary of hydrographic data from near bed currents

Hydrographic Summary	**ID277**	**ID282**
Deployment Date	May-Aug 2019	Aug-Sep 2019
Easting	201697	201674
Northing	764760	764722
Mean Speed (m/s)	0.0534	0.0515
Residual Speed (m/s)	0.007	0.007
Residual Direction (°G)	093	075
Tidal Amplitude Parallel (m/s)	0.095	0.084
Tidal Amplitude Normal (m/s)	0.037	0.034
Major Axis (°G)	060	030

1.1 Site Details

The site is situated near Ardgour, in Loch Linnhe (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 a sea loch. The pen center locations are given in Table 3. These locations were used in the modelling.

Table 3. Details of the individual pen centre locations and net depths used in the modelling for Ardgour (Linnhe).

Pen	Easting	Northing	Net Depth (m)
1	201516.61	764695.94	16
2	201575.71	764649.77	16
3	201470.43	764636.84	16
4	201529.53	764590.67	16
5	201424.26	764577.74	16
6	201483.36	764531.57	16
7	201378.08	764518.64	16
8	201437.18	764472.47	16
9	201331.91	764459.54	16
10	201391.01	764413.37	16

2 MODEL DETAILS

Several sets of simulations were performed. The first set focussed on localised deposition of waste solids beneath the 120m pens for both the existing maximum consented biomass, 2500T, and the proposed temporary maximum biomass, 3000T, utilising the NewDepomod model, configured in the default parameter values specified by SEPA and using measured flow data to force the model. The second set of runs again looked at the local deposition around Ardgour at both the current consented maximum biomass and the proposed temporary increased amount but used flow fields from a regional hydrodynamic model (WeStCOMS2) to force a different particle tracking deposition model, UnPTRACK. Finally, a third set of runs, also using WeStCOMS2 and UnPTRACK, looked at the cumulative deposition arising from the site at Ardgour together with that from the neighbouring Gorsten site.

2.1 Particle Tracking: 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 1.20220131164515.1643647287
datatypes version: Final 1.20220131164505.1643647287
util version: v1.4.0-final-(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 69 m, the average depth of deployment ID277 as this made up the majority of the flowmetry file. The flowmetry file combined the data from ID277 and ID282; after merging and truncating the data, the combined record was 90 days in total.

2.1.1 Local Deposition: NewDepomod

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 both 2500T and 3000T 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.

Note that the model simulations applied the increased biomass for one year, whereas an increase is only sought for four months. The results presented here therefore present a considerable over-estimate of the likely impact of the requested temporary change.

2.2 Hydrodynamic Model: WeStCOMS2

For the cumulative deposition modelling, the hydrodynamic flow data used to force the UnPTRACK model were taken from WeStCOMS2 version 2 (West Scotland Coastal Ocean Modelling System; Aleynik et al., 2016; Davidson et al., 2021), a hydrodynamic model implemented in FVCOM (Finite Volume Community Ocean Model) and coupled with WRF (Weather Research & Forecasting Model). Version 2 became operational in April 2019. FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model developed by the University of Massachusetts School of Marine Science and the Woods Hole Oceanographic Institute (Chen et al., 2003). The model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure submodels. The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is presented using generalized terrain-following coordinates. 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.

The WestCOMS2 model has been evaluated against a range of oceanographic data across the Scottish continental shelf and found to perform well (Aleynik et al., 2016). A further comparison was made against current meter data collected at Ardgour (Table 2) and the model was found to perform satisfactorily at this location (Mowi, 2023).

2.2.1 Model Domain and Boundary Conditions

The WeStCOMS2 domain and mesh is shown in Figure 3, with the area around Ardgour (Linnhe) shown in Figure 4. The mesh is fixed and is not refined down to 25 m specifically in the area of the cages, since the focus of the WestCOMS2 model is on regional oceanography. The use of the WeStCOMS2 model here is on the interaction of deposited material between neighbouring sites, although local deposition at Ardgour from the simulation is also presented. Note also that the concentrations of deposited wastes on the seabed were calculated on a regular grid using 50m x 50m squares, comparable to the diameter of a pen, not on the hydrodynamic model unstructured mesh. The hydrodynamic mesh is reasonably well resolved in the Ardgour area (Figure 4) and is adequate for modelling regional dispersion of particulate wastes over spatial scales of 50 m to several kilometres. The spatial resolution of the model varied from 50 m in some inshore waters to 3.5 km along the open boundary. In total, the model consisted of 99,999 nodes and 177,236 triangular elements.

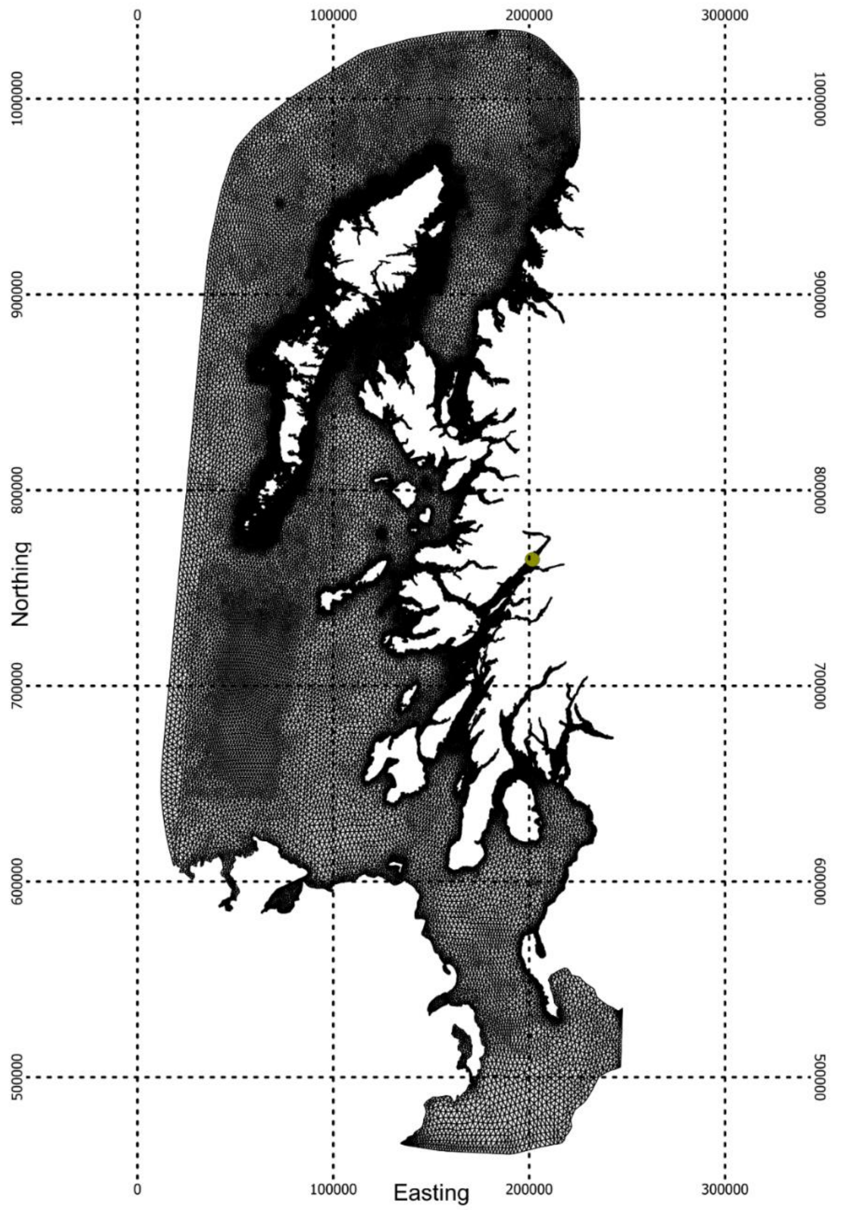

Figure 3. The WeStCOMS2 domain and mesh used in the Ardgour (Linnhe) modelling.

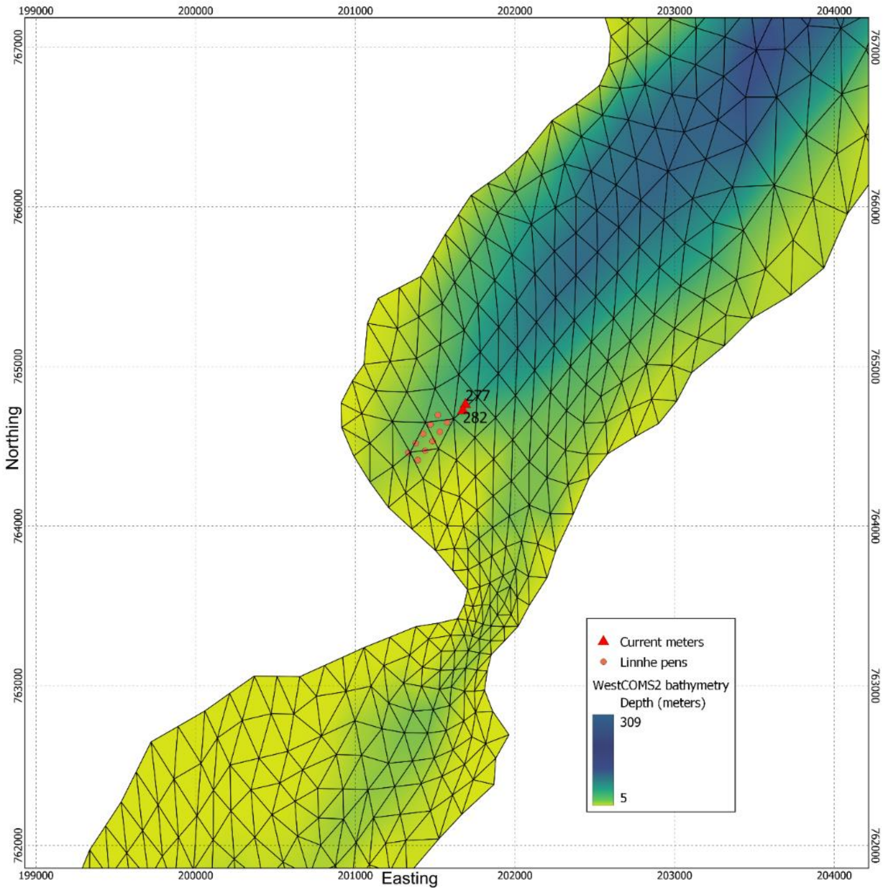

Figure 4. The model mesh in the area around the Ardgour (Linnhe) site with bathymetry. The pen locations (●) and current meter positions (▲) are indicated.

The WeStCOMS2 model bathymetry is shown in Figure 5. The open lateral boundaries are forced with output from a relatively high resolution (2 km) North-East Atlantic ROMS operational model (Aleynik et al., 2016). Tides at the boundaries are derived from the Oregon State University inverse barotropic tidal solution. Fresh-water discharge and sea-surface forcing are supplied from a coupled regional Weather Research Forecasting (WRF v4, Aleynik et al., 2016). The WeStCOMS2 model is run with 10 equally-spaced sigma layers.

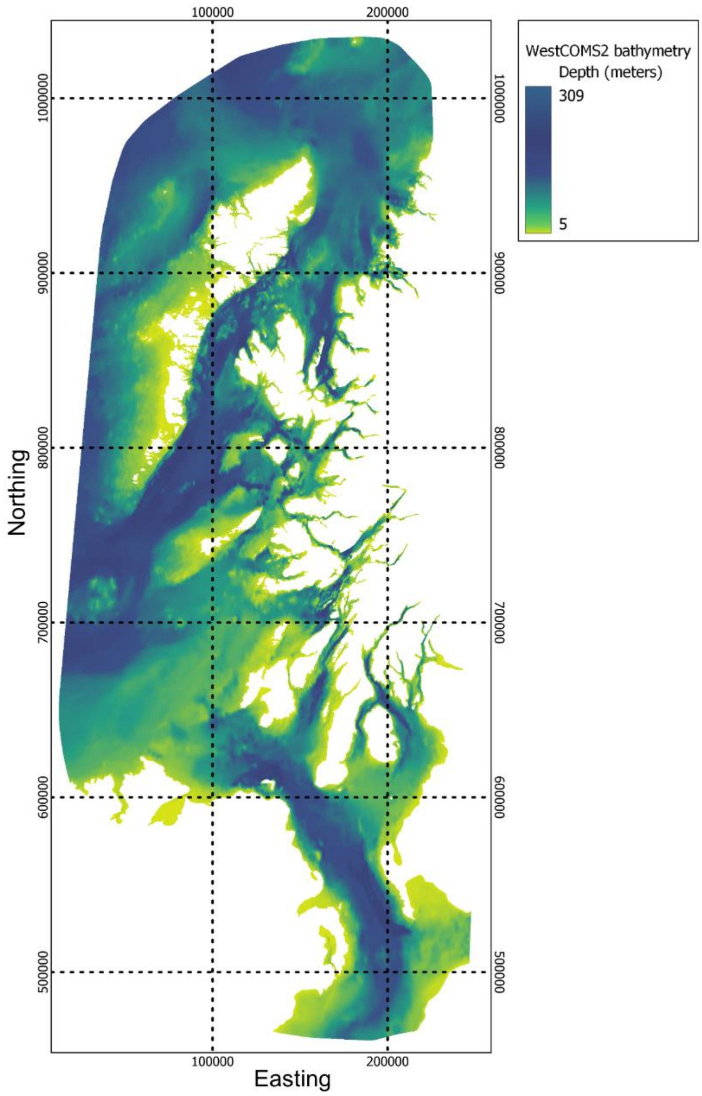

Figure 5. Bathymetry (meters), in the WeStCOMS2 domain.

2.2.2 Hydrodynamic Model Calibration

The hydrodynamic model was compared against current data and seabed pressure data, measured at Ardgour (Linnhe) using Acoustic Doppler Current Profilers (ADCP). Data are available at three locations (Figure 2) from:

(i) 23th May – 16th August 2019 (ID277)
(ii) 27th August – 29th September 2019 (ID282)

In total, the data extends over 115 days. Data was downloaded for the model for the same period as the observations and the modelled surface elevation and velocity at the two data locations were evaluated against the observed data. The comparison between modelled flow at the deployment locations with the measured data has been reported previously (Mowi, 2023); the model was found to perform satisfactorily for forcing particle-tracking simulations.

2.3 Particle Tracking Model: UnPTRACK

For the particle tracking component, Mowi's in-house model UnPTRACK (Gillibrand, 2021) was used. The model used the hydrodynamic flow fields from the WeStCOMS2 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., 2016) 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.

2.3.1 Local Deposition: UnPTRACK

The model was configured similarly to the standard default approach as specified by SEPA in the modelling guidance published in January 2022 (SEPA, 2022). The site was modelled for a maximum biomass of both 2500T and 3000T 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). However, these runs differ from the SEPA default method as variable bathymetry which better reflects the profile of the seabed below the farm was used rather than flat bathymetry, and hydrodynamic flow fields from WestCOMS2 were used instead of single-point current meter data.

UnPTRACK uses the underlying WeStCOMS2 mesh and bathymetry to simulate particle dispersal. The velocity fields taken from the hydrodynamic model are interpolated spatially and temporally to the particle location at each time step. The particle tracking model uses a time step of 60 s. However, concentrations of particle deposition are calculated in post-processing on a regular grid of 50m x 50m square cells, comparable to the diameter of a pen.

Particulate resuspension is modelled as follows: when a particle reaches the seabed due to its settling velocity, 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:

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

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, t_p is the age of the particle since settlement on the seabed and λ is a timescale for consolidation. With this approach, the probability of particle erosion increases with the excess shear stress, but decreases as the time since settlement increases. This reflects a likelihood that as particles remain on the seabed they become consolidated into the sediment layer and therefore less likely to be resuspended. The parameters c_r, τ_{bc} and λ are tuning coefficients that can be used to calibrate the deposition model. For the simulations presented in §3.2 and §3.3, values of c_r = 0.2, τ_{bc} = 0.02 Pa and λ = 4 days were used. A bed roughness scale of z_0 = 0.01 m was used to calculate the bed shear stress from the local current speed.

Mirroring the standard default NewDepomod approach, UnPTRACK 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).

2.3.2 Cumulative Deposition: UnPTRACK

Cumulative modelling runs were undertaken for Ardgour and the near-by site at Gorsten using the UnPTRACK particle tracking model. This was to check for any interactions between the footprints from the sites. A temporary maximum biomass increase at Gorsten is also being sought, so these runs were done using both the existing maximum biomass of 2500T and the proposed temporary increased maximum biomass of 3000T at both sites. Results were analysed over the final 90 days, with the mean deposition rate across the model domain being calculated and the footprint area being delimited by the 250 g m^{-2} contour, mirroring the approach used in the NewDepomod model runs.

Again, the increased biomass was applied and deposition modelled for one year, rather than the short four month temporary increase being sought. The model results are therefore almost certainly over-estimates of any consequent impact.

3. RESULTS

3.1 Local Deposition: NewDepomod

The modelled footprints for the Ardgour farm using the SEPA standard default method are shown for the existing and proposed temporary increased biomass (Figure 6). The area of the footprint for the current consented maximum biomass (2500T), as defined by the deposition rate of 250 g m^{-2}, was 758,125 m^2 (Table 4). The maximum 90-day mean deposition was 10,464.7 g m^{-2}. The intensity of deposition was 798.5 g m^{-2} which is well below the critical value of 2,000 g m^{-2}. The values in Table 4 show that the predicted footprint area only increases by 4.3% (for a whole year of production) when the biomass is increased by the proposed 500T.

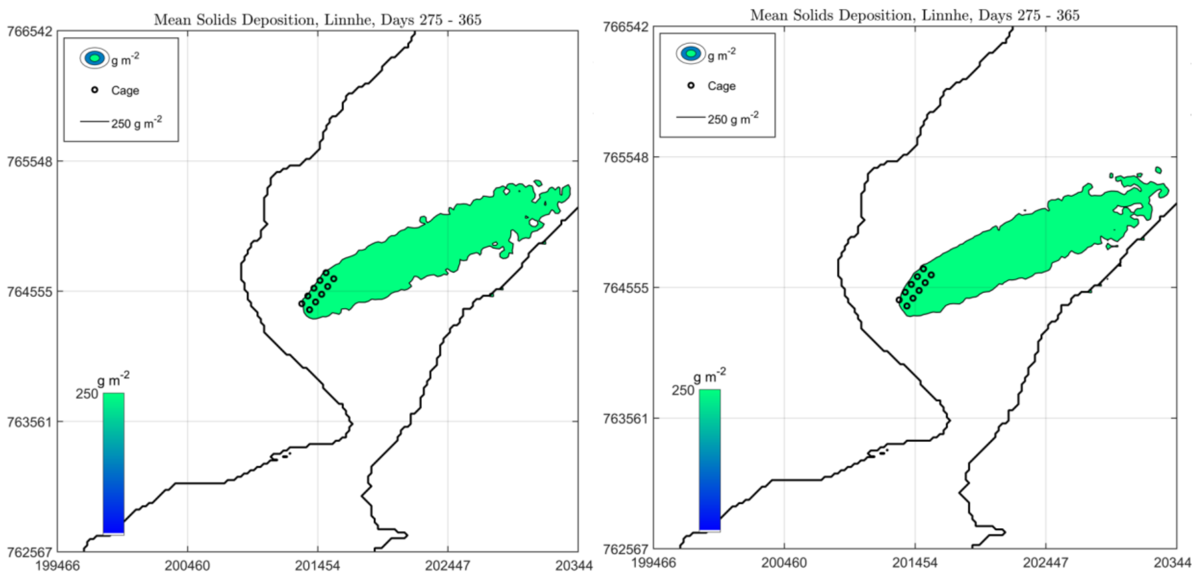

Figure 6. The modelled footprints at Ardgour (Linnhe) for the current maximum biomass of 2500T (left) and the proposed temporary biomass increase to 3000T (right), using the SEPA standard default method.

Table 4. Summary of results for Ardgour for the consented biomass and proposed temporary biomass increase, using the SEPA standard default method.

NewDepomod Results Summary			% increase
Maximum Biomass (T)	2,500	3,000	20
Feed Load (T/year)	6,388	7,665	20
Solid Waste Release Rate (kg day^{-1})	2,795	3,354	20
Allowable Mixing Zone (km^2)	0.154887	0.154887	0
Modelled Footprint (km^2)	0.758125	0.790625	4.3
Mean Footprint Deposition (g m^{-2})	798.5	978.7	22.6

3.2 Local Deposition: UnPTRACK

Mowi's in-house particle tracking model, UnPTRACK, was also used to simulate the solids deposition from Ardgour, using realistic bathymetry and hydrodynamic flow fields from WestCOMS2 model instead of the flat bathymetry and single-point current meter flow used by NewDepomod. This was thought to give a more realistic footprint for the site. Table 5 shows the results from the runs performed using UnPTRACK. The results show a substantially smaller footprint than the NewDepomod standard default approach. This shows that there was only a 10% increase in footprint area from the current consented biomass of 2500T and the proposed temporary increase to 3500T, substantially lower than the allowed 15% change. Figure 7 shows the footprints generated by the UnPTRACK runs, using the 250 g m^{-2} depositional contour to delineate the footprint.

Note that the 250 g m^{-2} contour presented in Figure 7 has not been calibrated against IQI data for this model area or configuration (realistic bathymetry, spatially-varying flows) and is presented here as a guide only, to allow the potential impact of the temporary biomass increase to be estimated. The 10% increase in footprint area arises after one-year of deposition at the increased biomass, rather than the proposed four months.

Table 5. Summary of results for Ardgour for the consented biomass and proposed temporary biomass increase, using the WestCOMS2 hydrodynamic flow fields with UnPTRACK and the 250 g/m^2 contour as a proxy for 0.64 IQI.

WeStCOMS2-UnPTRACK Results Summary			
			% increase
Maximum Biomass (T)	2,500	3,000	20
Feed Load (T/year)	6,388	7,665	20
Solid Waste Release Rate (kg day^{-1})	2,795	3,354	20
Allowable Mixing Zone (km^2)	0.154887	0.154887	0
Modelled Footprint (km^2)	0.175000	0.192500	10.0
Mean Footprint Deposition (g m^{-2})	4794.2	5255.0	9.6

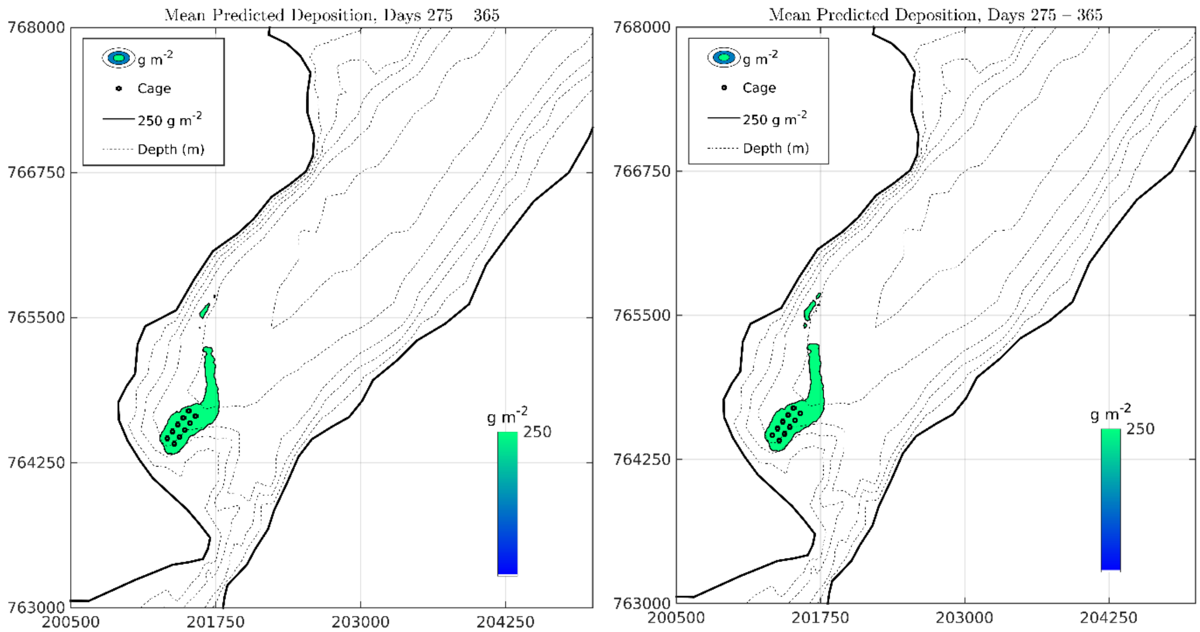

Figure 7. The modelled footprints at Ardgour (Linnhe) for the current maximum biomass of 2500T (left) and the proposed temporary biomass increase to 3000T (right), using the WestCOMS2 hydrodynamic flow fields with UnPTRACK.

Results from this simulation are also presented using a contour of 1490 g/m^2 to delineate the footprint (Figure 8) instead of 250 g/m^2. This value is taken from the model calibration for the recent Stulaigh South application where a deposition rate of 1490 g/m^2 was found to equate to an IQI of 0.64 at the neighbouring Stulaigh site (Mowi, 2022). Whilst we recognise that this calibration was not obtained from data local to Loch Linnhe, it does result in a footprint consistent with recent monitoring data (discussed below). The modelled footprint area for 2500 tonnes biomass is well within the allowable mixing zone, with only a 7% increase in area and 13% increase in intensity predicted for 3000 tonnes (Table 6).

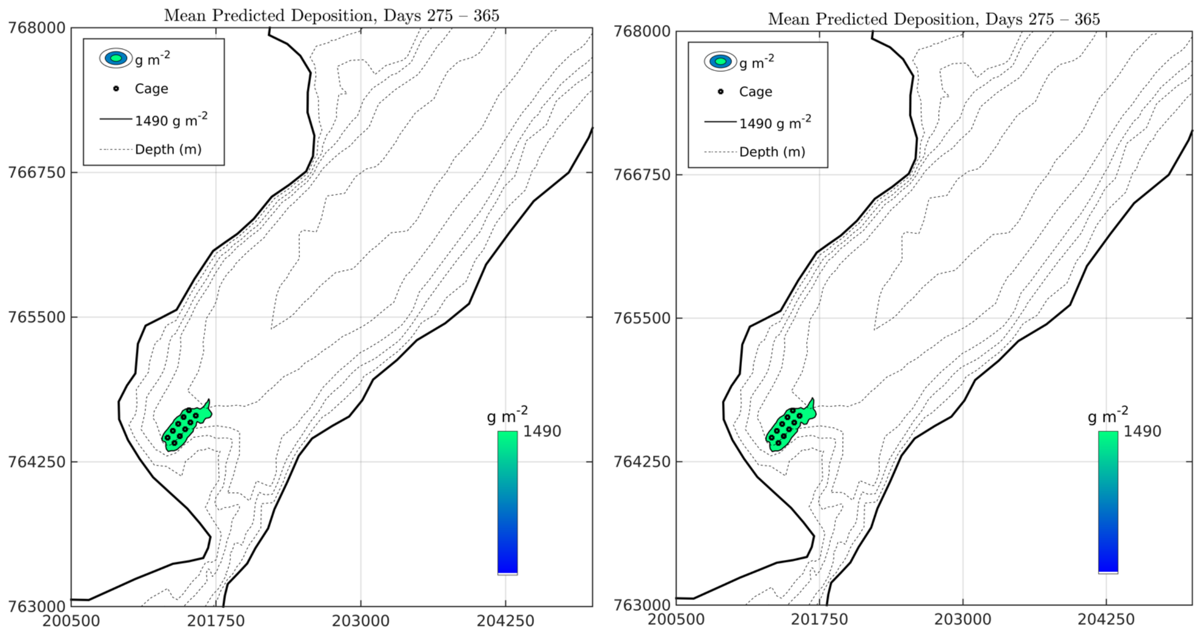

Figure 8. The modelled footprints at Ardgour (Linnhe) for the current maximum biomass of 2500T (left) and the proposed temporary biomass increase to 3000T (right), using the WestCOMS2 hydrodynamic flow fields with UnPTRACK and the 1490 g/m² contour.

Table 6. Summary of results for Ardgour for the consented biomass and proposed temporary biomass increase, using the WestCOMS2 hydrodynamic flow fields with UnPTRACK and the 1490 g/m² contour as a proxy for 0.64 IQI.

WeStCOMS2-UnPTRACK Results Summary			% increase
Maximum Biomass (T)	2,500	3,000	20
Feed Load (T/year)	6,388	7,665	20
Solid Waste Release Rate (kg day^{-1})	2,795	3,354	20
Allowable Mixing Zone (km^2)	0.154887	0.154887	0
Modelled Footprint (km^2)	0.080000	0.085625	7
Mean Footprint Deposition (g m^{-2})	9,782.8	11,073.8	13

The previous three benthic surveys conducted at Ardgour all passed with a classification of "Satisfactory" (Table 7). These surveys were undertaken in 2015, 2017 and 2019. Within these classifications, all pen edge and AZE samples passed (the AZE was set at 89 m from the pen edge). Mean deposition within the modelled footprints was relatively high in all results, but these benthic results show that the modelled intensity does not correspond to pen edge failure, and the modelled footprint area is consistent with the compliant AZE results.

Table 7. Benthic survey summary for Ardgour

Survey date	Site Classification	Biology		Chemistry
		Cage edge	AZE	
09/07/2019	Satisfactory	Pass	Pass	Pass
05/05/2017	Satisfactory	Pass	Pass	Pass
01/07/2015	Satisfactory	Pass	Pass	Pass

3.2.1 Solids Deposition and Sensitive Features

Two sensitive features have been identified to be potentially at risk from influence from the site due to their proximity to Ardgour. The locations of these features are listed in Table 8. Figure 9 shows that the protected marine features (PMF) are not within the boundary of the modelled NewDepomod footprint for either biomass consent. The results indicate that the sensitive features should not be negatively impacted by solids waste deposition.

Table 8. Table of identified features close to the Ardgour site

Feature Name	Easting	Northing
Horse Mussel Beds	203812	765703
Flame Shell Beds	203785	765646

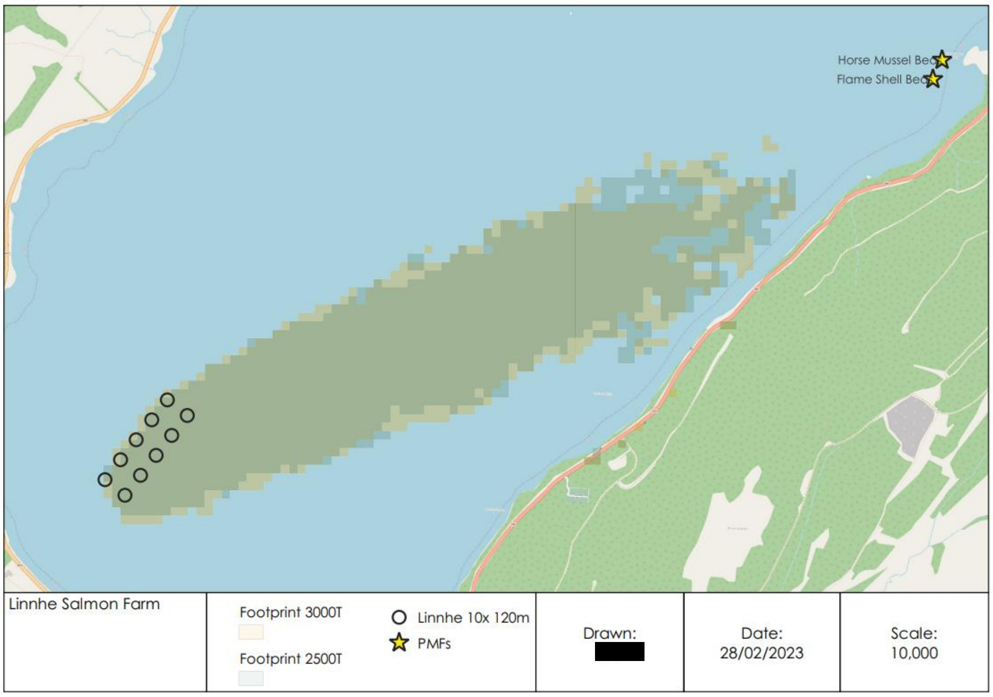

Figure 9. Identified PMF locations and the NewDepomod footprint for both the existing consented biomass of 2500T and the proposed temporary increase to 3000T at the Ardgour site. Locations of the Horse Mussel Beds PMFs and Flame Shell Beds PMF are indicated by the yellow stars.

3.3 Cumulative Predictions for Loch Linnhe

Cumulative particulate deposition arising from Ardgour (Linnhe) and its neighbouring site, Gorsten, was modelled using both the existing maximum consented biomass and proposed temporary maximum consented 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 10). The figure shows the deposition from the sites at lower levels than the standard 250 g m^{-2} contour, demonstrating that even at low levels there is unlikely to be depositional interaction between the two sites.

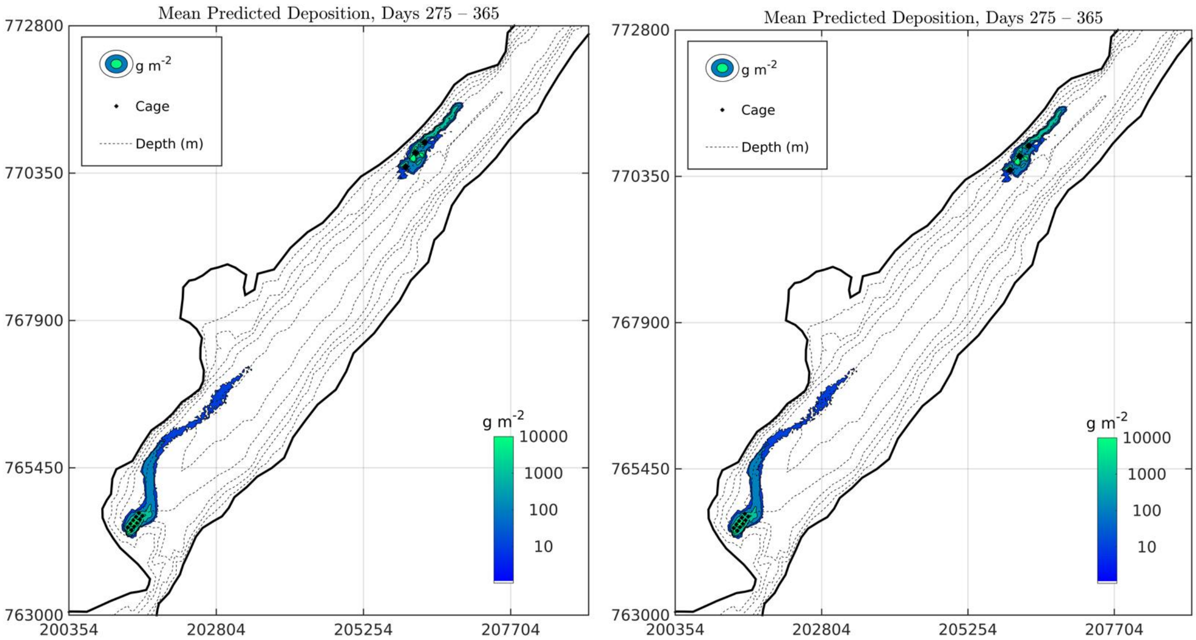

Figure 10. Predicted mean solids deposition over 90 days from the sites at Ardgour and Gorsten for both the existing consented biomasses (left) and proposed temporary increased maximum biomasses (right) using the nominal feed rate (7 kg/tonne/day) at each site.

4. SUMMARY AND CONCLUSIONS

The temporary biomass increase of 500 tonnes requested for consent at the Ardgour site and the associated feed loading (Table 4), has been shown to make relatively little difference to the footprint of the site (Table 4 – Table 6). The modelled increases to the footprint area and intensity are likely overestimates, since the proposed biomass increases is for a short period of 4 months only, whereas the modelling considered deposition at the increased rate for one year. The SEPA standard default method, which is designed to provide a conservative prediction of particulate deposition, suggested that a large depositional footprint will occur at the site, but this was thought to be unrealistic given the complicated hydrodynamics and bathymetry at Ardgour. The runs using UnPTRACK gave much more realistic results (Table 9) due to the use of the HD flow fields and variable bathymetry which better reflects the actual conditions at the site.

Table 9. Summary of Results from NewDepomod

Site Details	
Site Name:	Ardgour (Linnhe)
Site Location:	Ardgour
Peak Biomass (T):	3,000
Feed Load (T/year):	7,665
Pen Details	
Number of Pens:	10
Pen Dimensions:	120m Circumference
Working Depth (m):	16
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NewDepomod Results	
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Allowable Mixing Zone (m^2):	154,887
Maximum Deposition (g m^{-2}):	13,258.9
Modelled Footprint (m^2):	192,500
Mean Footprint Deposition (g m^{-2}):	5255.0

5. REFERENCES

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