Modelling of the Proposed Salmon Farm at Little Colonsay

Part 4. Waste

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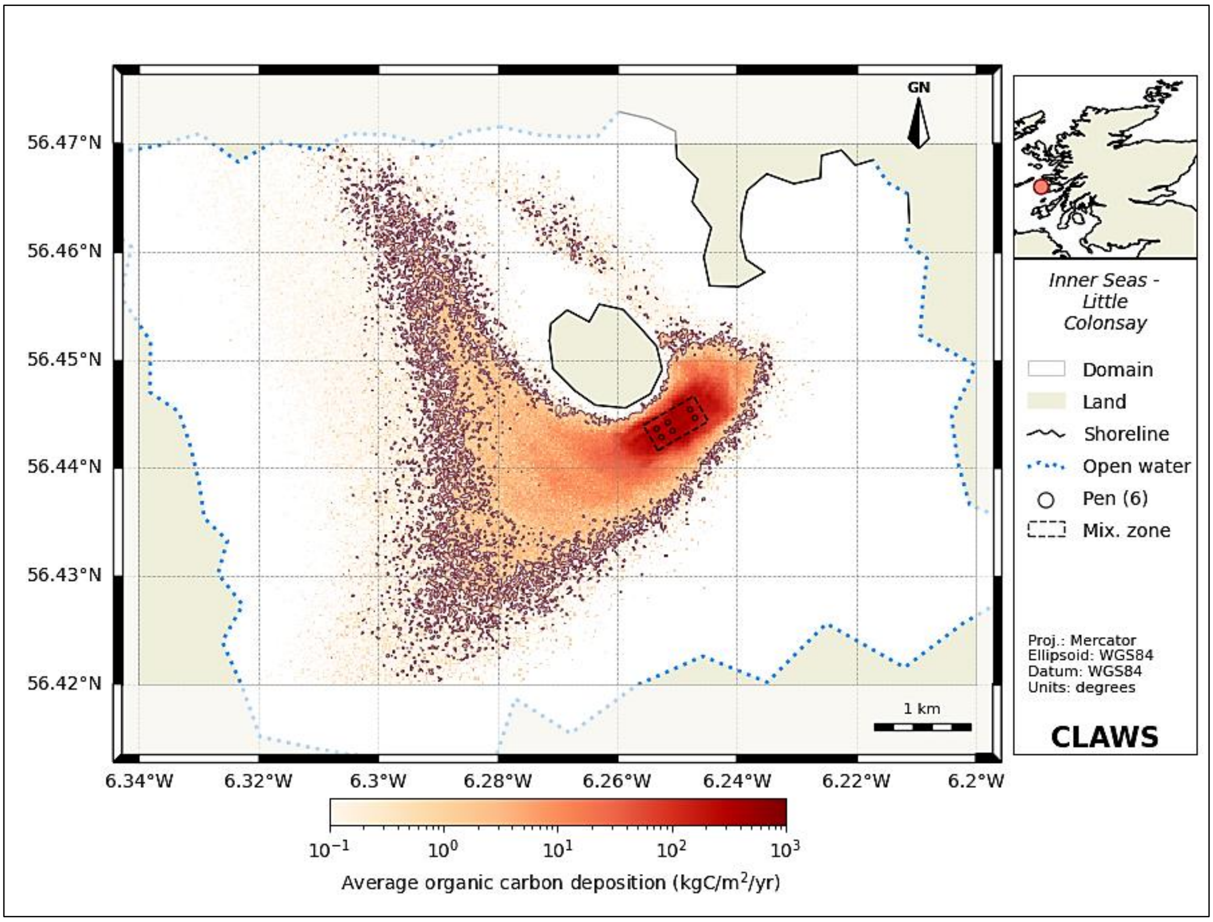

Executive Summary

A particle-based waste model has been developed for application in salmon farms in semi-enclosed sea lochs and open sea areas. The waste model is part of a suite of particle-based, open-source modules known as CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS_2023] has been applied to the proposed Bakkafrost farm at Little Colonsay. Other particle modules in the CLAWS repository include those to describe dissolved nutrients, bath treatments and sea lice issuing from finfish farms. The waste model calculates the flux of particulate organic matter emanating from the salmon farm and its impact on the benthic community. A 2D, depth-averaged, hydrodynamics model based on the Telemac code is used to drive the particle-based waste calculation and the model contains the influence of wind forcing. For the Lagrangian particle-tracking, the open-source code OpenDrift [OpenDrift_2023] has been used. Results show that the waste model can successfully predict the fate of waste material and illustrate key parameters such as the footprint of the deposition on the sea floor, waste density levels and benthic impact.

Underneath the farm pens, solid waste deposition peak intensities are likely to be in excess of the SEPA-recommended level of 2000 g/m^2. The waste deposition footprint for individual farms in the system was predicted to be up to 4.38-times greater than the SEPA-recommended Allowable Zone of Effect (AZE). However, the mean deposition fluxes were, in general, below the SEPA-recommended levels of 2000 g/m^2. Finally, the amount of organic carbon deposition for the combined farms in the Little Colonsay system is likely to lead to a significant degradation of the sea floor. The combined ECE and BII index predicts that the system will be "Category 1" and it is advised that "*…the most precautious approach to further fish farming development should be adopted.*" [GILL_2002].

About the Report Authors

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Tom is a chartered professional engineer with over 25 years' experience in applied computational mechanics. After a first degree in Environmental Engineering at the University of Strathclyde, Tom undertook a Ph.D in Vortex Shedding Flowmeter Pulsating Flow Computational Fluid Dynamics (CFD) Studies at the same university. Subsequently, he was awarded a JM Lessels scholarship from the Royal Society of Edinburgh for a one-year post-doctoral position at the Institute de Mécanique des Fluides de Toulouse, France in the field of numerical oceanography. The IMechE presented Tom with the Alfred Rosling Bennett Premium and Charles S Lake Award in 2003 for CFD in applied aerodynamics. In 2013 Tom returned from an EPSRC-funded sabbatical in the USA, where he carried out fundamental research in rarefied gas dynamics at the University of Michigan and the Lawrence Berkeley Laboratory in California. From 1994-2017 he was a Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the University of Strathclyde specialising in heat transfer, fluid mechanics and applied CFD. His work is reported in over 50 refereed journal and conference publications. He is currently a director at the engineering consultancy firm MTS-CFD.

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Vincent is an engineering consultant with background experience in fluid dynamics and computer science. He obtained his Masters engineering degree in Aeronautics and Aerospace at ISAE-ENSMA, Poitiers, France. Following an internship at the European Space Agency, Vincent undertook a Ph.D in high-speed re-entry physics at the University of Strathclyde under the supervision of Dr Tom Scanlon, where he developed an open-source platform to solve hypersonic continuum and rarefied flows that has since been used in 15+ countries. Vincent was a Postdoctoral Fellow at McGill University in Montreal, Canada from 2019-2021, where he co-led the development of a monolithic software system to simulate hypervelocity civilian craft, partnering with Ansys and Lockheed Martin.

Dr Matt Stickland *BSc PhD CEng FIMechE, Engineering Consultant, MTS-CFD.com*

After a first degree in Aeronautical Engineering at the University of Manchester, Matt worked for BAE Systems (Military Aircraft) at Warton in Lancashire in the Wind Tunnel Department working on projects which included EAP, EFA (Typhoon), Tornado and HOTOL. After leaving BAE in 1990 Matt worked for YARD Consulting Engineers in Glasgow modelling the heat and fluid flows in Advanced Gas Cooled reactors during on-load refuelling. In 1991 Matt accepted a senior lectureship in the Department of Mechanical Engineering at the University of Strathclyde where his research interest covered both experimental and computational heat transfer and fluid dynamics. He was awarded a PhD for his research into 3D imaging and its application to fluid flow visualisation. For his research in the field of experimental and computational fluid dynamics he was awarded the 2003 AR Bennett Premium/CS Lake Award and the 2004 T A Stewart-Dyer Prize/Frederick Harvey Trevithick Prize from the Institute of Mechanical Engineers. In 2022 Matt left the University of Strathclyde to take a directorship with the Engineering consultancy firm MTS-CFD. Matt is a Chartered Engineer and a Fellow of the Institute of Mechanical Engineers. He has published his research in over 100 papers in refereed journal and conference proceedings.

1 Introduction and motivation

This report has been prepared for Simon Cowell, by engineering consultants MTS-CFD, as part of hydrodynamic modelling services to consider the impact of particulate waste emanating from existing and proposed fish farms on the West Coast of Scotland. The report describes the application of a particle-based waste model to determine the deposition fluxes on the sea bed from the proposed Little Colonsay salmon farm. The waste model is part of a suite of particle-based, open-source modules known as CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS_2023]. Other particle modules in the CLAWS repository include those for dissolved nutrients, bath treatments, and parasitic salmon lice emanating from finfish farms.

Operational fish farms have the potential to affect the marine environment in several ways, via the release of waste in the form of dissolved nutrients, particulate organic matter, pesticides and live parasitic salmon lice.

Considering the particulate waste material being discharged from fish farms, this can be split into two components – uneaten feed pellets and faecal matter. Estimates for the total amount of waste (uneaten feed + faeces) amount to approximately 3% of the feed delivered [SEPA_2023]. This 3% waste consists of approximately 83% faeces and 17% uneaten feed [SEPA_2023].

Waste deposition on the sea bed may lead to deterioration of the physical and chemical conditions within the bed itself. In such cases, the sea bed can become organically enriched and anoxic causing distortions in the benthic fauna.

The eventual location of deposition on the sea bed will primarily depend on local bathymetry, water current, particulate settling velocity. In reaching the sea bed these particles may become incorporated into the sediment or may be resuspended into the water column by near-bed currents thus further dispersing them away from the cages. The rate at which solid deposition occurs is known as “flux” or “intensity”. Solid flux decreases with increasing distance from the farm as finer particles take longer to settle and are dispersed more widely

Allowable Zones of Effect (AZE’s or “mixing zones”) are defined as the area of sea bed in which SEPA will allow some exceedance of a relevant Environmental Quality Standard (EQS). The far-field AZE is equivalent to a 100 m margin around the group of cages representing the fish farm [SEPA_2023]. It is the outer boundary of the deposition footprint which is of primary interest from a modelling viewpoint as site-specific information can be used in a model to determine the shape and extent of the footprint.

There are no apparent Environmental Standards for sediment intensity. However, SEPA consider that [SEPA_SCRN_2023]:

- Underneath farm pens, an intensity of 2000 g/m^2 or less is likely to lead to an acceptable sea bed ecological outcome.
- At the edge of the mixing zone, an intensity of 250 g/m^2 or less is likely to lead to an acceptable sea bed mixing zone (AZE) outcome.

The waste model may be used to characterise the impact on the benthic community in three ways:

1. The deposition model can determine the area of the waste footprint, delimited by the deposition flux contour of 250 g/m^2 [SEPA_SCRN_2023]. This area can then be compared to the AZE, calculated from the 100 m farm margin.
2. The predicted mean and peak deposition fluxes within the waste footprint can be compared to the SEPA-derived acceptable value of 2000 g/m^2.
3. A Benthic Impact Index (BII) [GILL_2002] may be calculated by determining the footprint area of organic carbon from feed and faeces, delimited by the contour of 0.7 $kgC/m^2/year$. Above this critical value, it has been shown that the infaunal diversity of sediments is reduced, and the seabed can be considered 'degraded' [GILL_2002]. The BII can then added to the index linked to the dissolved nutrients addition (Equilibrium Concentration Enhancement – ECE) for a combined index to characterise the likely environmental impact.

2 Background data

2.1 *Site location at Little Colonsay and surrounding farms*

The focus of the waste modelling process is the proposed Bakkafrost salmon farm at Little Colonsay. Furthermore, the surrounding existing farms at Gometra, Tuath and Geasgill were also modelled to predict their likely impact. Figures 2.1 and 2.2 show the location of the Little Colonsay and surrounding farms, respectively. Table 2.1 shows the peak biomasses for the farms involved in the waste modelling study.

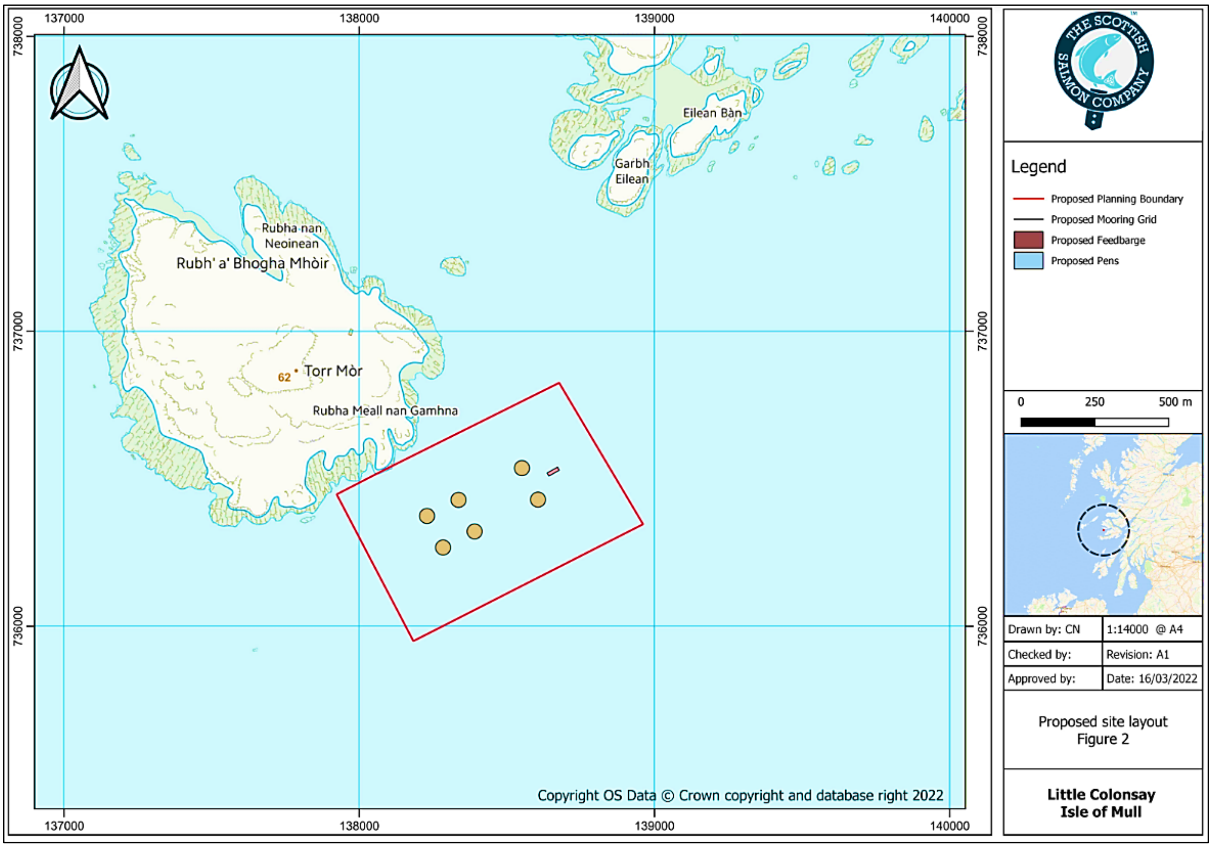

Figure 2.1 *Geographic location of the proposed Bakkafrost salmon farm at Little Colonsay (inset on lower right shows the overall location).*

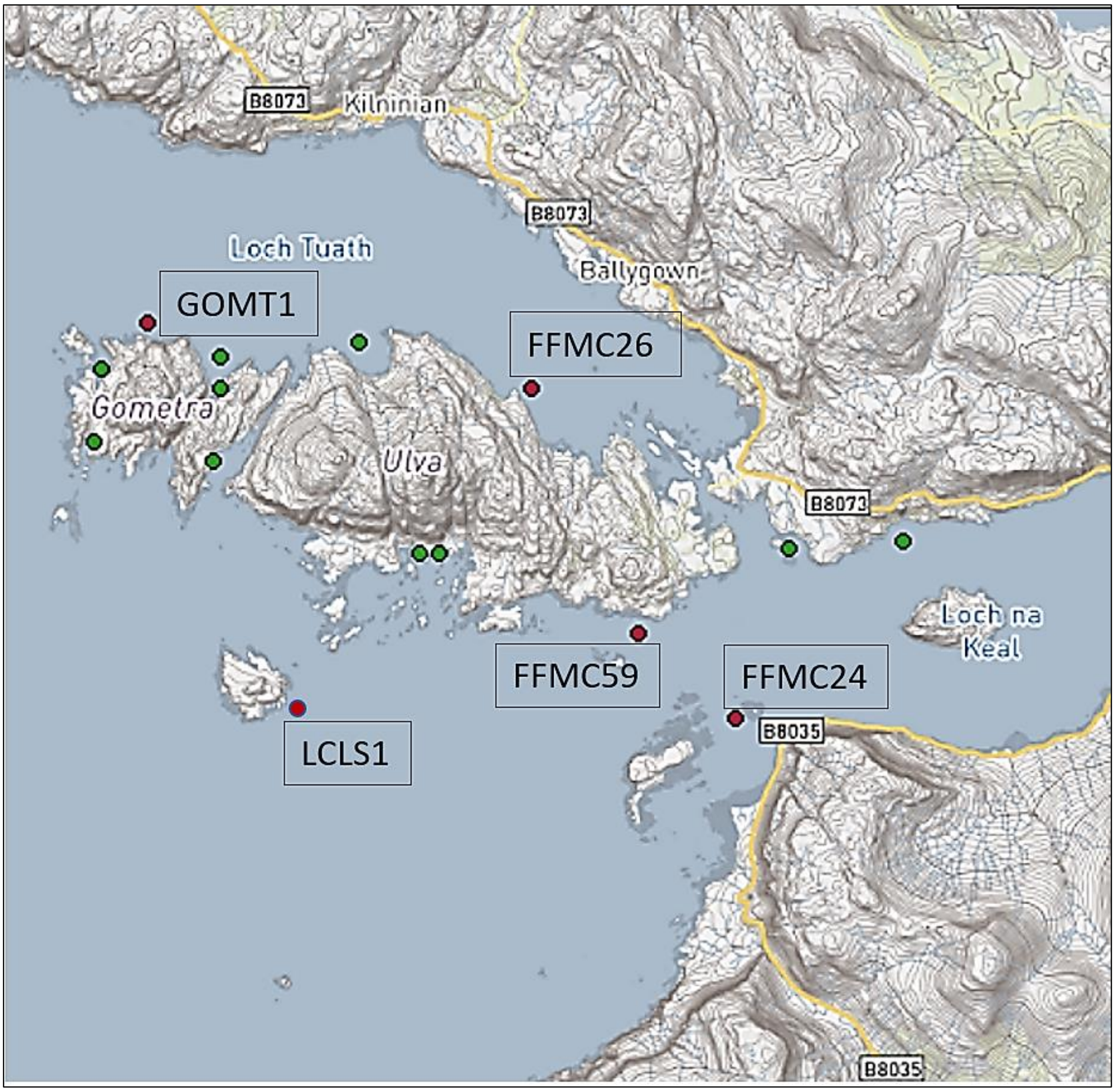

Figure 2.2 *Location of the 4 salmon farms in the waste model highlighted by red dots and shown in Table 1. Note that FFMC24 (Inch Kenneth) is discounted as it is out of production. Green dots are active shellfish farms. Farm locations taken from [AQUA_SCOT_2023].*

Table 2.1 *Salmon farm biomasses used in the waste calculation [SEPA_SCRN_2023].*

Site ID	Name	Biomass (tonnes)
LCLS1	Little Colonsay	2773
GOMT1	Gometra	1944
FFMC26	Tuath	850
FFMC59	Geasgill	2500

2.2 *Hydrodynamic data and validation at Little Colonsay*

A 2D, depth-averaged hydrodynamics model based on the TELEMAC code [ScanlonB_2023] is used to drive the particle-based waste dispersion calculation. The extent of the model is shown in Figure 2.3. Wind forcing is included in the hydrodynamics model based on weather data at 6-hourly intervals [ERA_2023] and the computational mesh in the vicinity of Little Colonsay is shown in Figure 2.4. The hydrodynamic modelling approach along with validation studies is described in full elsewhere, [ScanlonB_2023] and is only summarised here.

2.3 *Bathymetry data*

The bathymetry data for the present study have been collected from a range of different sources including publicly available data sets provided by Marine Scotland for the Scottish Shelf Model [SSM_2023], digitised Admiralty charts and bathymetry information from the UK's Digimap Ordnance Survey Collection [DOSC_2023]. The bathymetry used in the model is shown in Figure 2.5.

2.4 *Shoreline database*

The shorelines delineating land and water areas are obtained from the GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography) database [WESSEL_1996] [DAGESTAD_2018] and the highest possible resolution is applied. The shorelines were then constructed using the freely-available BlueKenue software [BLUEKENUE_2023].

2.5 *Modelling approach*

The modelling approach employed a coupled hydrodynamic and particle tracking method, whereby water currents in the region, modelled using the calibrated 2D hydrodynamic model, advected particles representing the waste solids (faeces and uneaten feed) around the model domain. Turbulent eddy diffusion was modelled using a random walk approach. Outputs from the modelling were derived to assess the flux of waste solids accumulating on the sea floor.

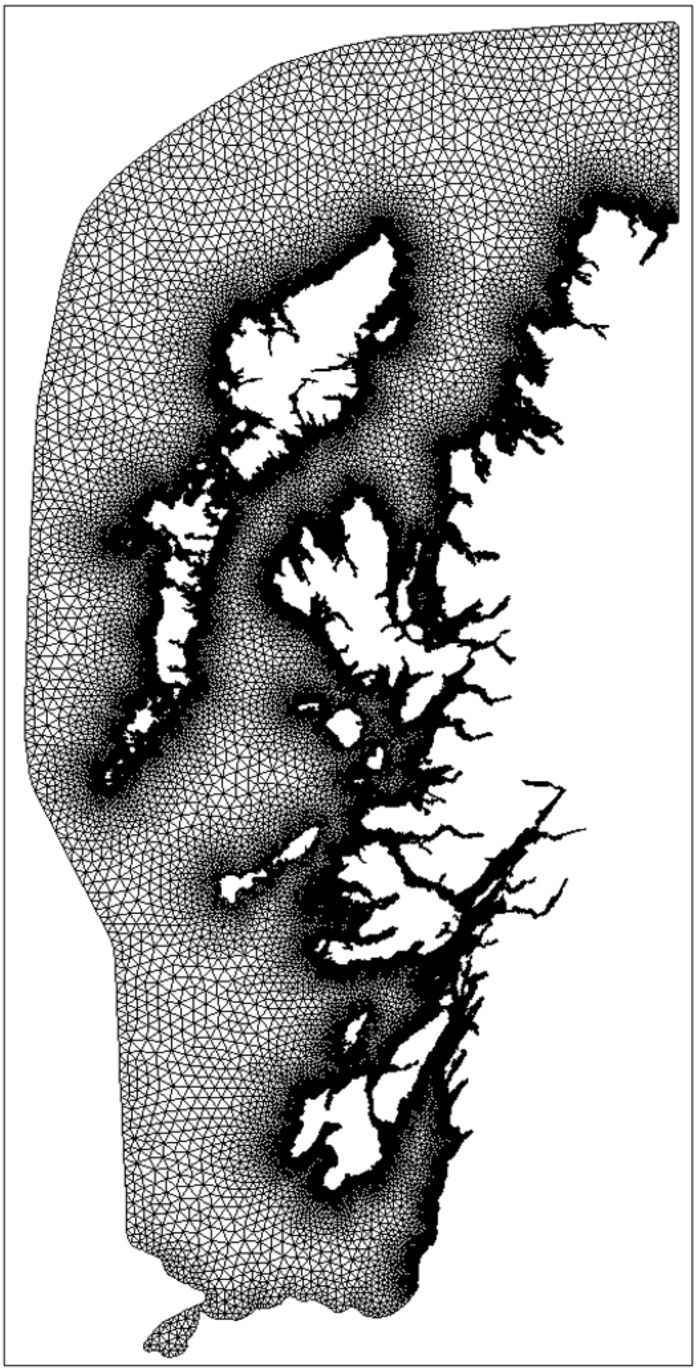

Figure 2.3 *Telemac hydrodynamic mesh and model extent.*

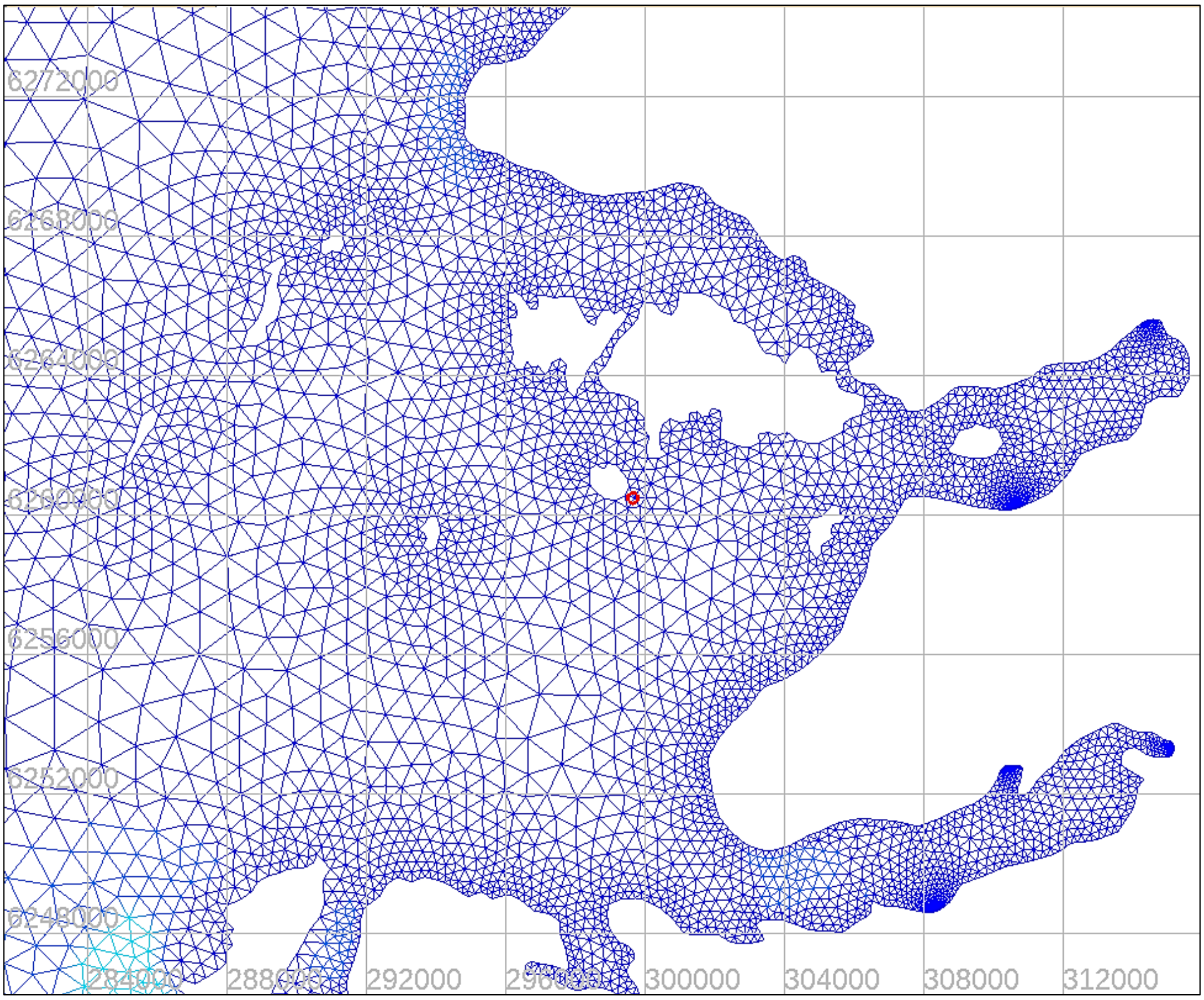

Figure 2.4 *Hydrodynamic mesh near Little Colonsay*. *The farm location is indicated by the red circle.*

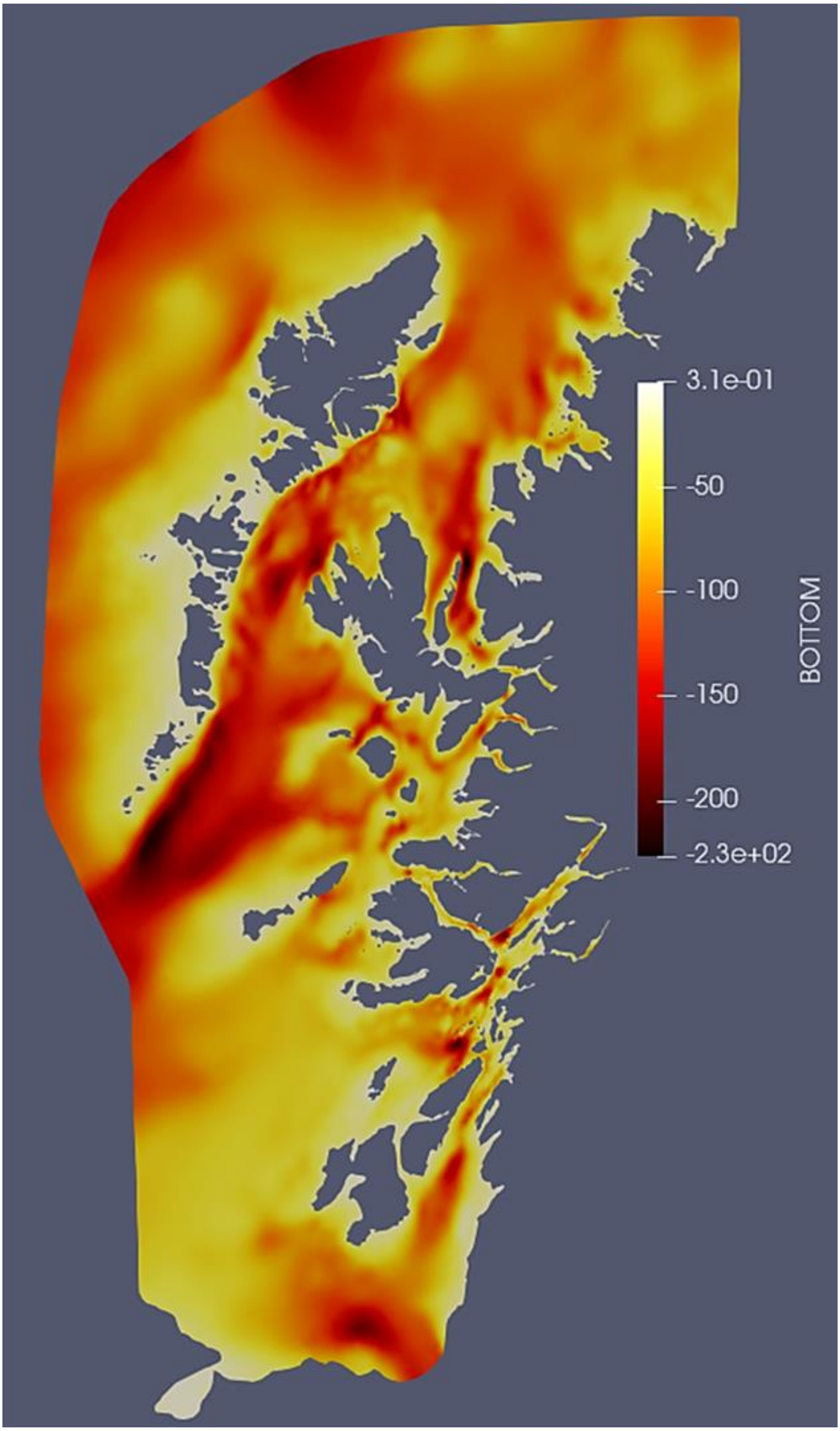

Figure 2.5 *West Coast model bathymetry (m).*

Additional validation of the 2D model was carried out using observed data captured by Bakkafrost [SSC_2022] at the proposed salmon farm at Little Colonsay, see [ScanlonB_2023] for further details. Figure 7 shows the Telemac hydrodynamic mesh in the area.

For the hydrodynamics, the model was "spun-up" during a 4-week period from 1st-31st May 2018. This was to fully develop the hydrodynamic fields prior to commencing the waste model study. The 2D waste model was then run for a period of 365 days from the 1st June 2018 to the 31st May 2019.

Figures 2.6 and 2.7 show snapshots of the typical flow patterns in the Little Colonsay area during flood and ebb tide events.

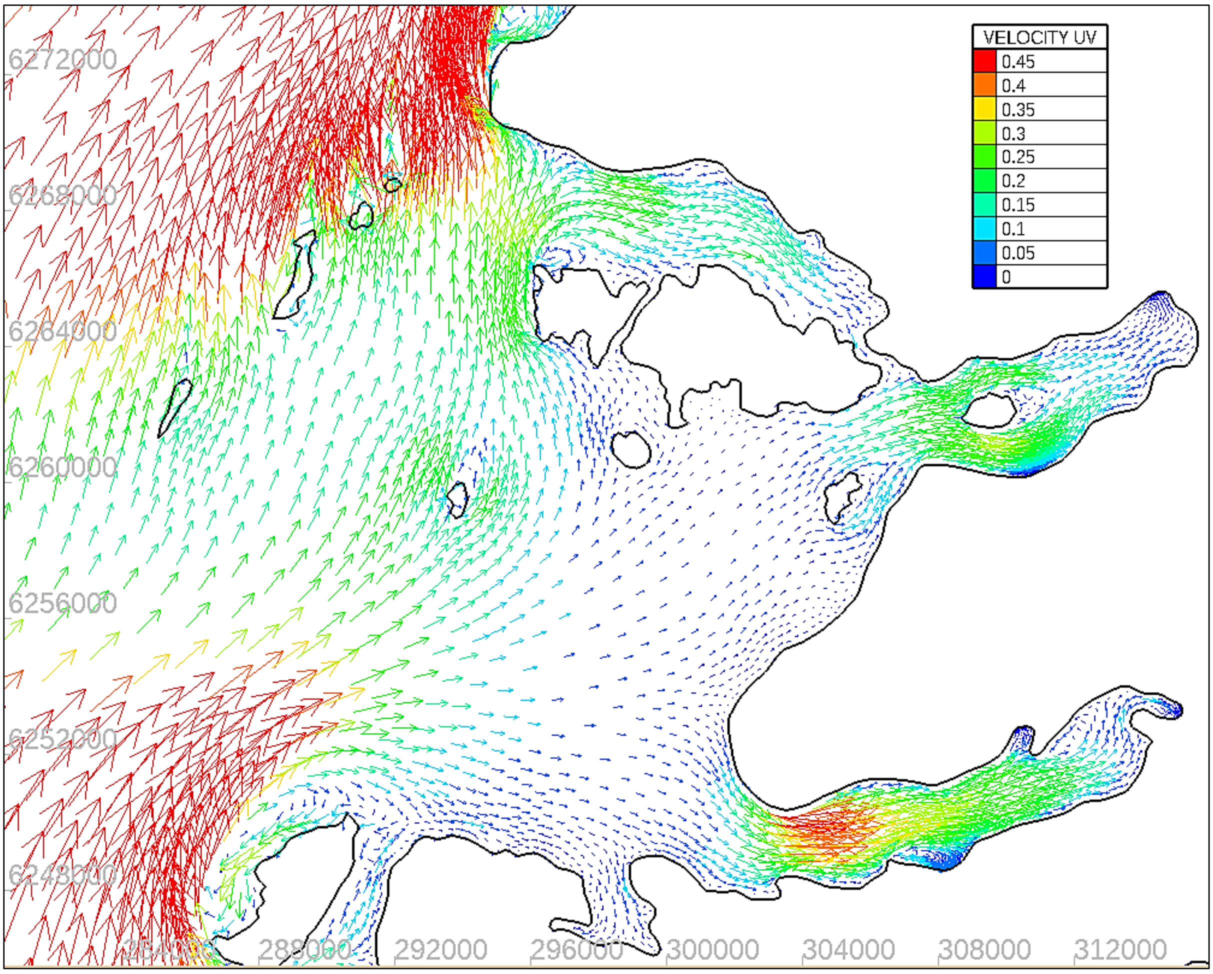

Figure 2.6 *Snapshot example of current velocity (m/s) during a flood tide.*

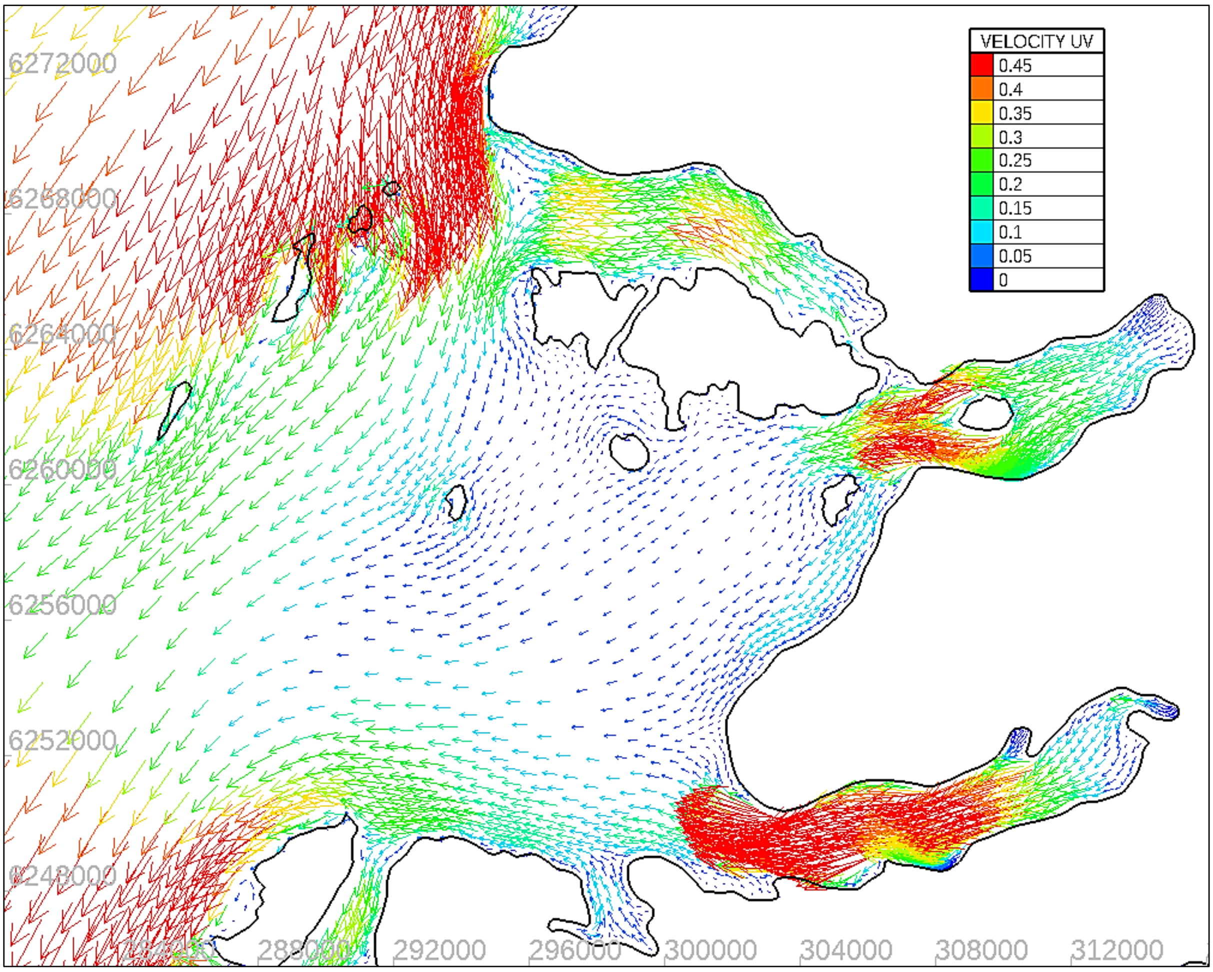

Figure 2.7 *Snapshot example of current velocity (m/s) during an ebb tide.*

3 Solids waste dispersion modelling

3.1 *Particle-tracking of waste solids*

For the Lagrangian particle-tracking the open-source software OpenDrift has been used [OpenDrift_2023]. The approach for waste solids is the same as for living organisms such as sea-lice, except that waste solids have no biological behaviour. Each particle in the model represents a quantity of faeces or uneaten feed of known mass, based on the salmon biomass of each farm. Particles are released at pen locations at regular intervals, according to a user-defined schedule. The number of particles released was 10 per pen per time-step based on the recommended value [Interim_NewDepomod_Guidance_2022]. The particles are then subject to advection, from the modelled flow fields, horizontal and vertical diffusion, sea bed deposition and possible resuspension. Concentrations of solids waste (known as "flux") on the sea bed can be calculated throughout the simulation and compared with relevant statutory standards. Here, we have modelled the dispersion of waste solids following a year-long feeding scenario at the proposed Little Colonsay farm and the existing farms Gometra, Tuath and Geasgill. These will illustrate the quantities of feed and faeces that are likely to accumulate in the marine environment.

The waste modelling study uses the parameters advised in the *SEPA Standard Default NewDepomod model* [Interim_NewDepomod_Guidance_2022]. 10 particles representing salmon faeces and 10 representing uneaten feed were released each hour from each pen from the 1st June 2018. This allowed the build-up of solids waste on the sea-bed to occur. Averaging of the flux of solids waste on the sea bed took place on an orthogonal sampling mesh of resolution 20 m × 20 m during the final 90-days of the study, i.e., from 1st March - 31st May 2019. It should be noted that the sampling mesh of 20 m × 20 m squares used in this study exceeds the SEPA-recommended value of 25 m × 25 m [Interim_NewDepomod_Guidance_2022] and will thus provide higher-resolution results.

3.2 *Waste modelling methodology*

The waste model, developed as part of the CLAWS software suite [CLAWS_2023], follows a similar strategy to other established salmon waste models such as NewDepomod [NewDepomod_User_Guide_2023] and UnPtrack [MOWI_UnPtrack_2023].

A flowchart to describe the CLAWS waste modelling approach is presented in Figure 3.1.

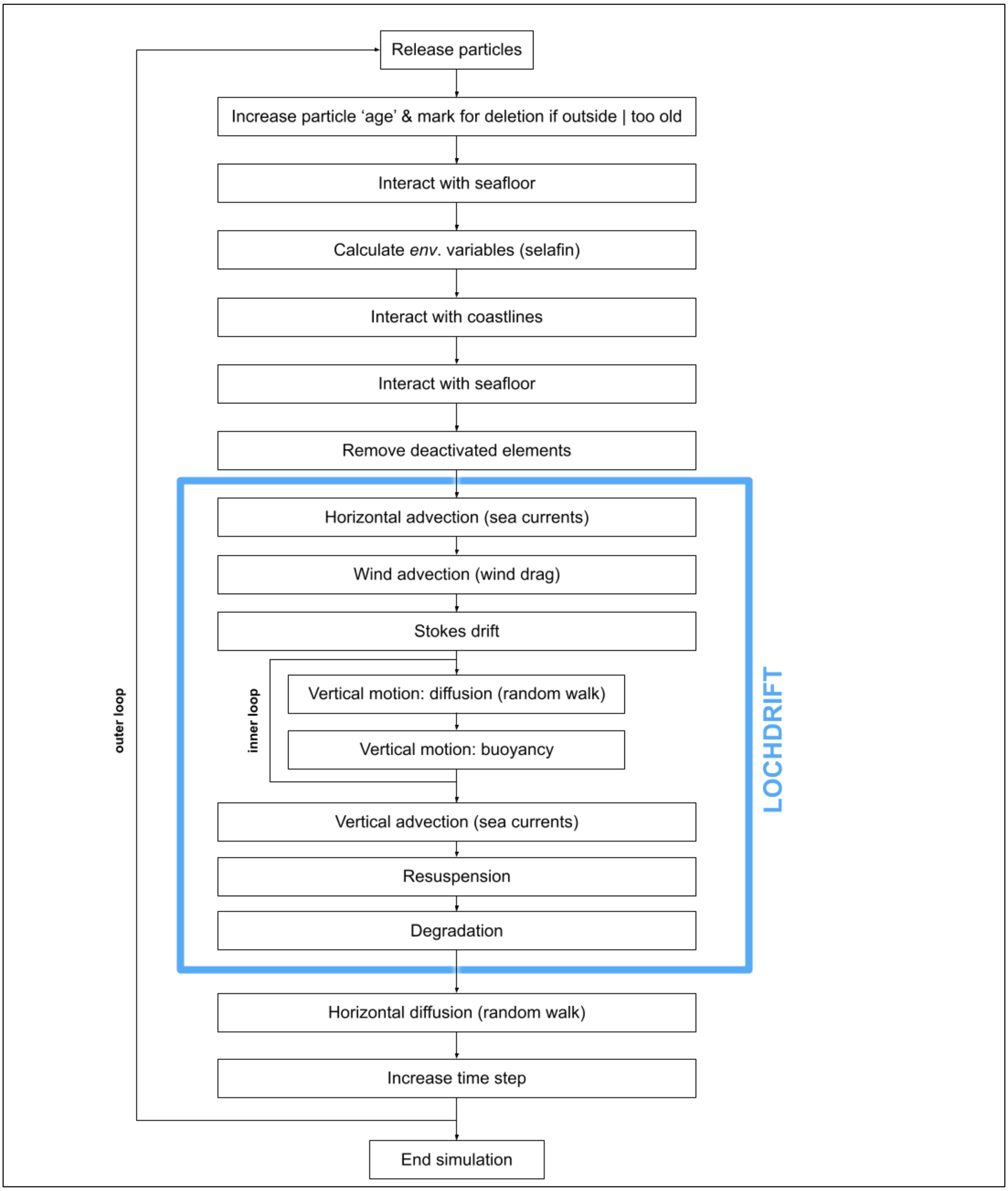

Figure 3.1 *CLAWS waste module flowchart.*

The physical processes and characteristics of the CLAWS waste model can be summarised as follows:

- **Horizontal advection**

Particles' horizontal and vertical motions are solved for separately in LochDrift (see Figure 3.1). A 4th order explicit Runge-Kutta temporal discretisation scheme is used to advect particles along the East and North directions.

- **Diffusion**

Random dispersion is computed using one of the following random walk models [NewDepomod_User_Guide_2023]:

  - Lattice model

$$x^{n+1} = x^n + \sqrt{2\, k_x \Delta t}\, R_b$$

$$y^{n+1} = y^n + \sqrt{2\, k_y \Delta t}\, R_b$$

$$z^{n+1} = z^n + \sqrt{2\, k_z \Delta t}\, R_b$$

  - Uniform model

$$x^{n+1} = x^n + \sqrt{6\, k_x \Delta t}\, R_u$$

$$y^{n+1} = y^n + \sqrt{6\, k_y \Delta t}\, R_u$$

$$z^{n+1} = z^n + \sqrt{6\, k_z \Delta t}\, R_u$$

where $x^n / y^n / z^n$ and $x^{n+1}/y^{n+1}/z^{n+1}$ represent the East, North and relative depth position of a particle at two successive time instants, respectively. k_x, k_y and k_z are the horizontal and vertical diffusion coefficients, Δt is the time-step, R_b is a random integer number equal to -1 or 1, and R_u is a random number drawn uniformly between -1 and 1. For the work contained in this report, the Lattice model was applied.

- **Law of the wall**

For 2D depth-averaged hydrodynamics, a log-law profile is emulated where the East and North components of the current velocity vector, v_x and v_y, are multiplied by a scaling factor f that depends on the depth layer of the particle:

- Sea surface layer (down to 60% of depth): f = 1.14
- Middle layer (60% of depth down to 95% of depth): f = 1
- Bed layer (95% of depth and below): f = 0.743
- Seafloor: f = 0

In addition, the vertical velocity component v_z is assumed to be zero in 2D.

- **Terminal velocity and vertical dispersion**

Buoyancy effects on the particle's vertical motion are modelled as

$$z^{n+1} = z^n + \Delta t \, (v_{sink} + v_z)$$

where v_{sink} is the terminal velocity (also called still-water settling velocity or sinking velocity) that is sampled from a Gaussian distribution [Interim_NewDepomod_Guidance_2022]. Settling velocities for feed and faeces are set according to the NewDepomod Draft Guidance document [Interim_NewDepomod_Guidance_2022]. Any resuspended particles are considered to have the properties of finer sediment and particle properties such as length scale and settling velocity are modified accordingly [Interim_NewDepomod_Guidance_2022].

- **Deposition**

A particle deposits on the seafloor when its relative depth is less or equal than the local seafloor depth. Its relative depth is then kept equal to the seafloor depth until resuspension.

- **Resuspension**

The probability of resuspension of deposited particles can be computed as [MOWI_App3_2021]:

$$P_{resuspension} = cr\ (\tau - \tau_{bc})\ e^{-\frac{t_{res}}{\lambda_c}},$$

where cr is a resuspension constant, τ_{bc} is the critical erosion stress threshold, and λ_c is a consolidation time scale. This probability is compared to a random number ranging between 0 and 1, R, and a particle is resuspended if $P_{resuspension} > R$. The vertical diffusivity of resuspended particles is set to [Interim_NewDepomod_Guidance_2022]

$$k_z = 3 \cdot 10^{-4}\ v^{-0.762}$$

where v is the local sea current velocity defined as

$$v = \sqrt{v_x^2 + v_y^2}$$

The frictional stress at the seabed, τ, can be written as [MOWI_App5_2021]

$$\tau = \rho_{water}\ c_D v\ |v|$$

where the sea water density ρ_{water} is computed according to [Fofonoff_Millard_1983], and c_D is the drag coefficient that can either be set to be a constant value or according to the following formula [MOWI_App5_2021]

$$c_D = \left(\frac{\kappa}{log\ \left(\frac{z_b + z_0}{z_0}\right)} \right)^2$$

where κ is the Karman constant equal to 0.41, z_0 is seabed roughness length scale, and z_b is the height above the bed of the lowest velocity point (i.e., first layer mid-height at the particle's location in 3D or half of the bed layer thickness (taken as 5% of relative depth) in 2D).

- **Degradation / Decay**

The half-life of feed pellets and faeces is considered infinite [Interim_NewDepomod_Guidance_2022].

- **Summary of the constants used in the models**

Parameter	Meaning	Value	Units	Reference
cr	Resuspension constant	10	-	[MOWI_App3_2021]
τ_{bc}	Critical erosion stress threshold	0.02	Pa	[Interim_NewDepomod_Guidance_2022]
λ_c	Consolidation time scale	4	days	[MOWI_App3_2021]
z_0	Seabed roughness length scale	0.01	m	[MOWI_App3_2021]
z_r	Particle resuspension height	0.35	m	[MOWI_App3_2021]
k_x, k_y	East and North diffusion coefficients	0.1	m^2/s	[MOWI_App3_2021]
k_z	Vertical diffusion coefficient	0.001	m^2/s	[MOWI_App3_2021]

3.3 *Waste feed, faeces and organic Carbon content.*

The waste feed, faeces and organic carbon content levels are detailed in this section and follow the SEPA guidance [Interim_NewDepomod_guidance_2022] as follows:

1) Farms should be modelled at peak biomass for the entire period. Peak biomass should be used to calculate solids waste, including waste feed and faeces.

Recommended default values used in this work:

Feed requirement = 7kg feed per tonne biomass per day

Feed Water Percentage = 9%

Feed Waste Percentage = 3%

Feed Absorbed Percentage = 85%

Feed Carbon Percentage = 49%

Faeces Carbon Percentage = 30%

2) *Waste Feed Calculation and Default Parameters*:

   Waste solids (kg) = (1 – feed water content) x feed wastage rate x feed load (kg). Typical values for the water content of the feed and the feed wastage rate are 0.09 (i.e., 9%) and 0.03 (3%) respectively.

3) *Calculating the discharged carbon specifically requires a small addition*:

   Waste solids (carbon) (kg) = (1 – feed water content) x feed carbon content x feed wastage ate x feed load (kg) where a typical value for the feed carbon content is 0.49 (49%).

4) *Excreted Solids Calculation and Default Parameters*:

   Excreted solids (kg) = (1 – feed water content) x (1 - feed wastage rate) x (1 - feed absorbed rate) x feed load (kg) where a typical value for the absorption rate is 0.85.

5) *Calculating the excreted carbon specifically requires a small modification*:

   Excreted solids (carbon) (kg) = (1 – feed water content) x (1 - feed wastage rate) x (1 – feed absorbed rate) x faeces carbon content x feed load (kg) where the faecal carbon content is typical taken to be 0.3 (i.e., 30%).

4 Presentation of results

4.1 *Little Colonsay waste footprint*

The deposition model has been used to calculate the area of waste footprint, delimited by the mean solids deposition flux contour of 250 g/m^2 [SEPA_SCRN_2023]. This area can then be compared to the AZE, calculated from the 100 m farm margin, which has a value of 180,000 m^2. The 250 g/m^2 footprint area predicted by the waste model was 663,600 m^2. This means that the mean waste solids footprint area is likely to be a factor of *3.69 times greater* than the SEPA statutory AZE limit.

Figure 4.1 shows the footprint of the mean solids deposition at Little Colonsay. The deposition pattern is mainly to the south-west of the farm, arcing around the island to the north-west in a clockwise manner. Figure 4.2 shows a zoomed image of the footprint with the 100 m AZE (mixing zone) highlighted by the dashed line and the 250 g/m^2 and 2000 g/m^2 contours shown by the solid lines.

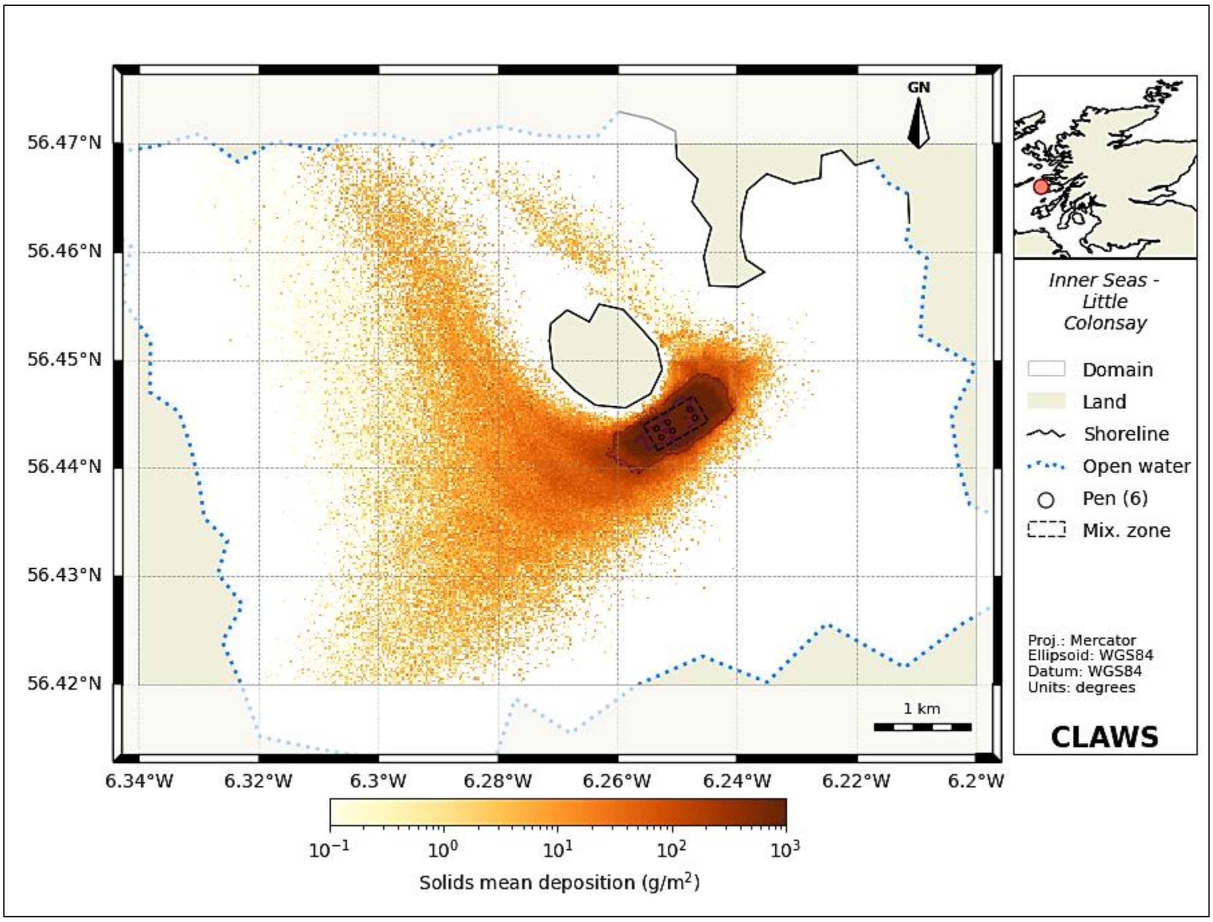

Figure 4.1 *Waste solids (feed and faeces) mean deposition footprint (g/m^2) for the proposed Bakkafrost farm at Little Colonsay. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 2773 tonnes.*

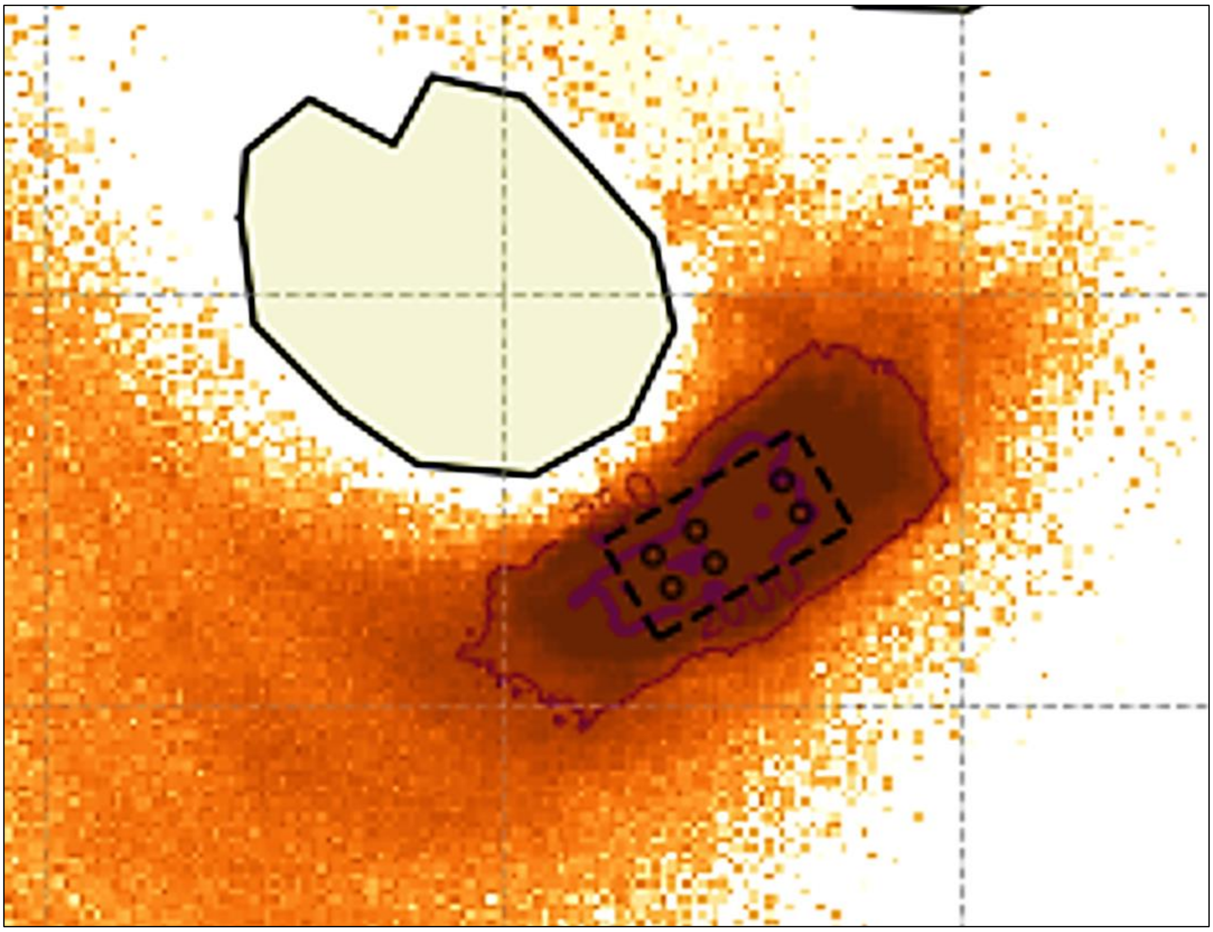

Figure 4.2 *Zoomed image of waste solids (feed and faeces) mean deposition footprint (g/m^2) for the proposed Bakkafrost farm at Little Colonsay. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. Dashed line shows the extent of the Allowable Zone of Effect (AZE or mixing zone). Outer solid line shows the limit of the 250 g/m^2 contour and the inner purple line denotes the 2000 g/m^2 contour.*

4.2 *Little Colonsay mean and peak deposition fluxes*

The mean deposition intensity (flux) within the 250 g/m^2 contour was calculated as 1414 g/m^2. This is below the SEPA-recommended value of 2000 g/m2 [SEPA_SCRN_2023]. However, peak value within the 250 g/m^2 contour was found to be 3915 g/m^2, a level which is described as *"less likely to lead to an acceptable sea bed ecological outcome"* [SEPA_SCRN_2023].

4.3 *Little Colonsay Benthic Impact Index (BII)*

A Benthic Impact Index (BII) [GILL_2002] may be calculated by determining the footprint area of average particulate organic carbon from feed and faeces, delimited by the contour of 0.7 kgC/m^2/year. Above this critical value, it has been shown that the infaunal diversity of sediments is reduced, and the seabed can be considered 'degraded' [GILL_2002]. The BII can then then added to the index linked to dissolved nutrients addition (Equilibrium

Concentration Enhancement – ECE) for a combined index to characterise the likely environmental impact.

The footprint area of organic carbon was calculated as 6.14 km^2 and the extent of this area is shown in Figure 4.3.

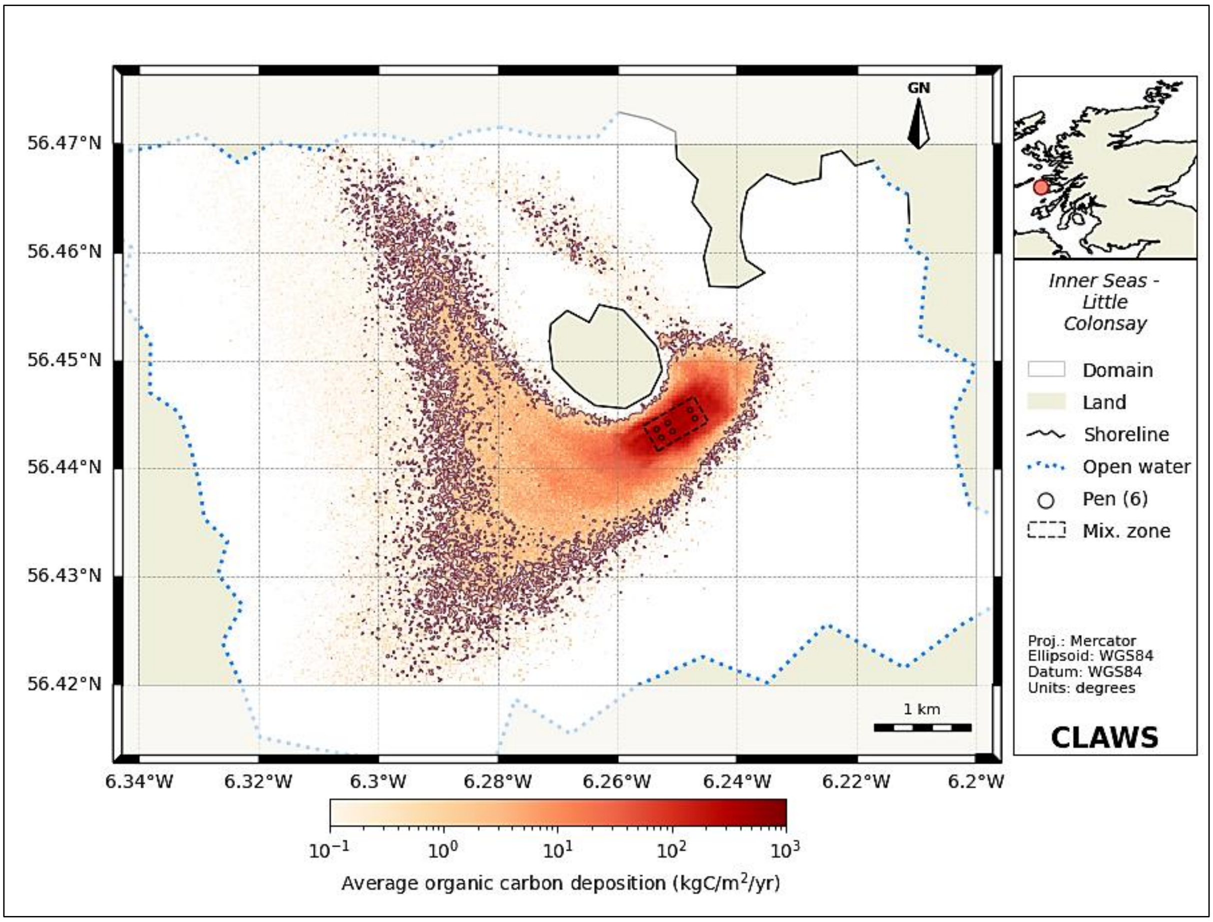

Figure 4.3 *Footprint area of particulate organic carbon (kgC/m^2/year) for the proposed Bakkafrost farm at Little Colonsay. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. Contour shown is delimited by the value of 0.7 kgC/m^2/year. Above this critical value, it has been shown that the infaunal diversity of sediments is reduced, and the seabed can be considered 'degraded' [GILL_2002]. Area of the contour footprint is 6.14 km^2.*

The surface area of the inner seas around Little Colonsay has been estimated previously as 141.84 km^2 [MTS_CFD_Nutrients_2023], including Loch na Keal. This area is shown in Figure 4.4. The Benthic Impact Index (BII) is calculated by dividing the organic carbon footprint size by the sea loch surface area to give a percentage degradation. Dividing the organic carbon footprint area (6.14 km^2) by the surface area of the inner seas (141.84 km^2) gives a percentage degradation of 4.3 %.

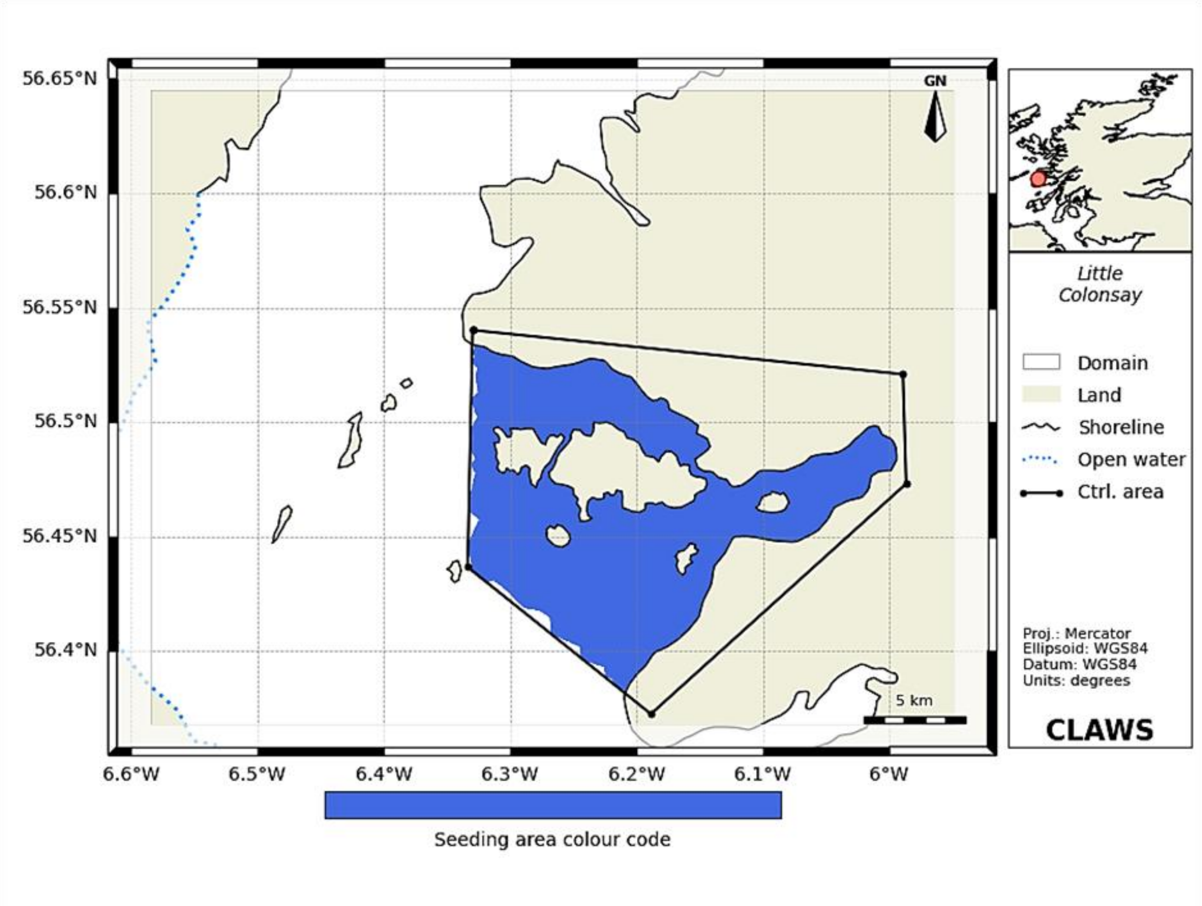

Figure 4.4 *Surface area of the inner seas around Little Colonsay, including Loch na Keal (blue zone – 141.84 km^2) [MTS_CFD_Nutrients_2023].*

Table 4.1 shows the index of nutrient enhancement, derived from predicted levels of equilibrium concentration enhancement (ECE) for dissolved nitrogen. The nutrient enhancement index was calculated in a separate MTS-CFD report [MTS_CFD_Nutrients_2023] as level 2.

Table 4.1 *Index of nutrient enhancement [GILL_2002.]*

Predicted ECE for nitrogenous nutrients arising from fish farming (µmol l^{-1})	Nutrient enhancement index
> 10	5
3 – 10	4
1 – 3	3
0.3 – 1	2
< 0.3	1
0	0

The Benthic Impact Index (BII), predicted to show reduced Infaunal Trophic Indices (ITI) as a result of the deposition of carbon organic matter from fish farms, is shown in Table 4.2. For the Little Colonsay farm the organic carbon footprint percentage degradation was 4.3%, leading to a BII value of 4.

Table 4.2 *Benthic Impact Index [GILL_2002].*

Percentage area of sea-bed predicted to be 'degraded' by organic deposition (%)	Benthic impact index
> 10	5
3 – 10	4
1 – 3	3
0.3 – 1	2
< 0.3	1
0	0

The ECE and BII indices are then added together to give a single combined index for each individual farm, as shown in Table 4.3. The resultant single index, scaled from 0 – 10, is subsequently used to provide an indication of the relative sensitivity of a sea loch system to further fish farming development. Sea lochs with the highest combined index value are considered most sensitive to the expansion of fish farming operations and as such are considered as Category 1 areas.

Table 4.3 *Combined ECE and BII indices [GILL_2002].*

Combined 'nutrient enhancement' and 'benthic impact' indices	Category
7 – 10	1
5 – 6	2
0 – 4	3

This derivation of Categories on the basis of a combined index is such that the modelling results for Category 1 sea lochs are towards the top of the scale for either nutrient enhancement or benthic impact. Category 1 areas will necessarily have at least one individual index of 4 or greater (3 - >10 $\mu mol\ l^{-1}$ nutrient enhancement or 3 - >10 % degraded sea-bed area). In these areas the most precautious approach to further fish farming development should be adopted [GILL_2002]. Category 2 areas have at least one individual index value of 3 or greater and a degree of precaution should also be applied to consideration of further fish farming development in these areas [GILL_2002].

For the Little Colonsay farm the combined ECE and BII index was 2 + 4 = 6, thus the Little Colonsay farm is likely to have a Category 2 environmental impact and thus "*a degree of precaution should be applied to consideration of further fish farming development in this area.*" [GILL_2022].

4.2 *Waste analysis at Gometra, Tuath and Geasgill.*

A similar analysis to that described in section 4.1 for Little Colonsay has been carried out for the other existing farms in the local system at Gometra, Tuath and Geasgill. This analysis provides details of the waste footprint characteristics, mean and peak solids waste flux (g/m^2) and the Benthic Impact Index (BII).

Figures 4.5 to 4.10 show images of the footprint extent for the existing farms and Table 4.4 summarises waste solids impact on the sea bed for all farms in the system.

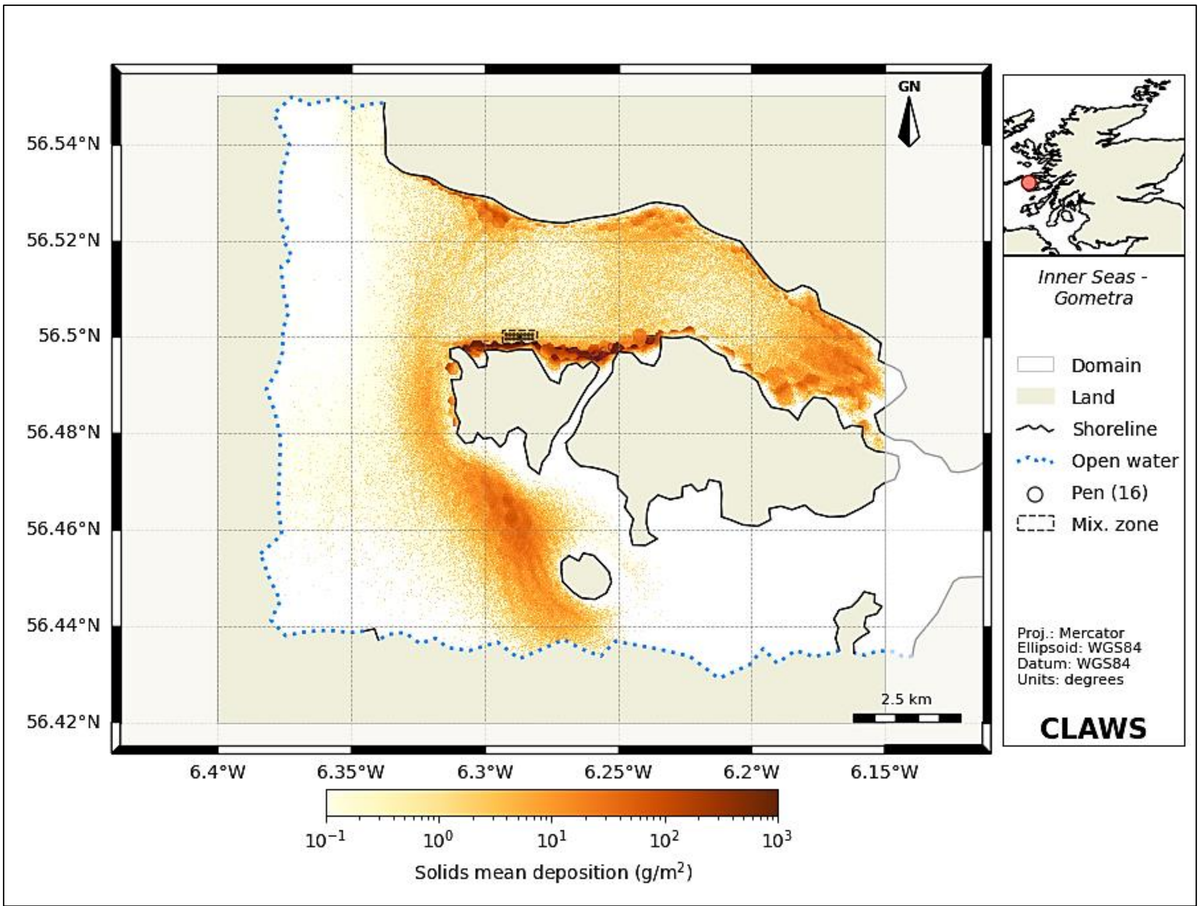

Figure 4.5 *Waste solids (feed and faeces) mean deposition footprint (g/m^2) for the existing farm at Gometra. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 1944 tonnes.*

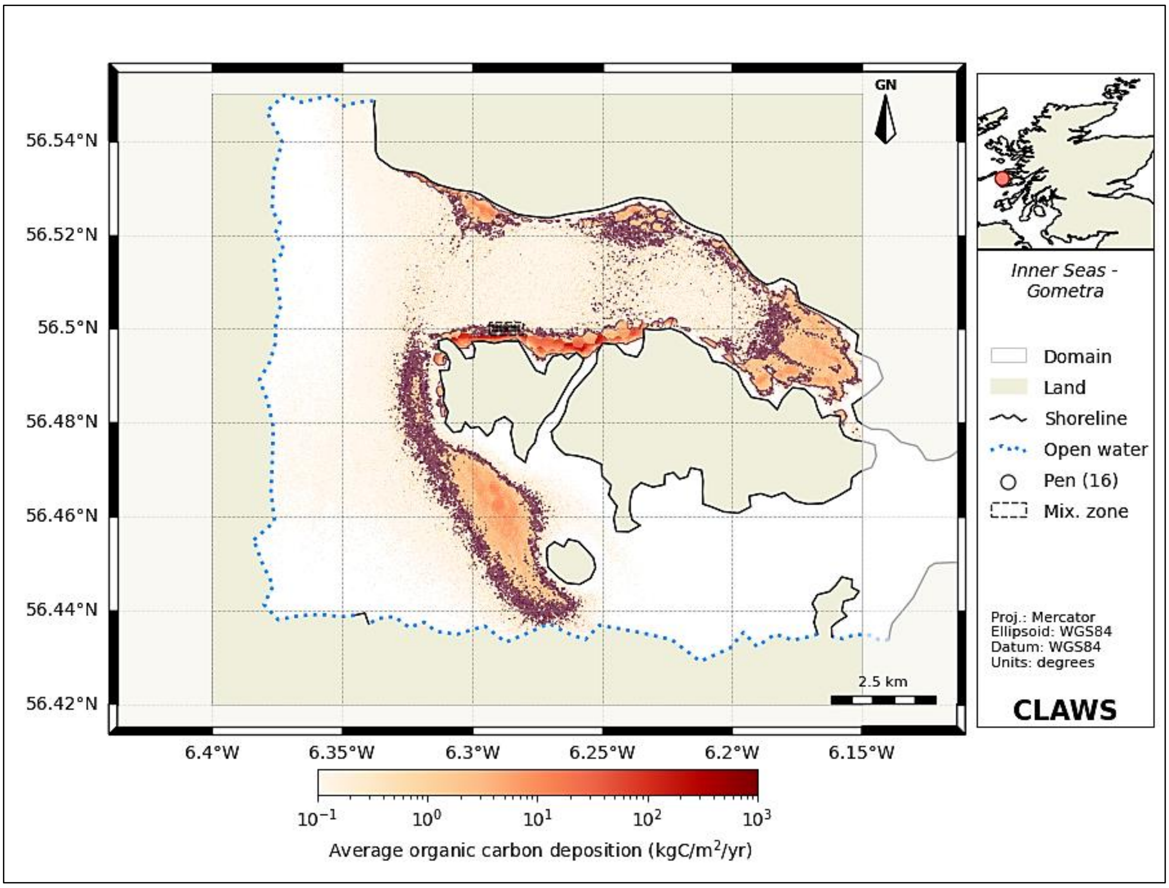

Figure 4.6 *Footprint area of particulate organic carbon (kgC/m^2/year) for the existing farm at Gometra. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. Contour shown is delimited by the value of 0.7 kgC/m^2/year. Above this critical value, it has been shown that the infaunal diversity of sediments is reduced, and the seabed can be considered 'degraded' [GILL_2002]. Area of the contour footprint is 13.98 km^2.*

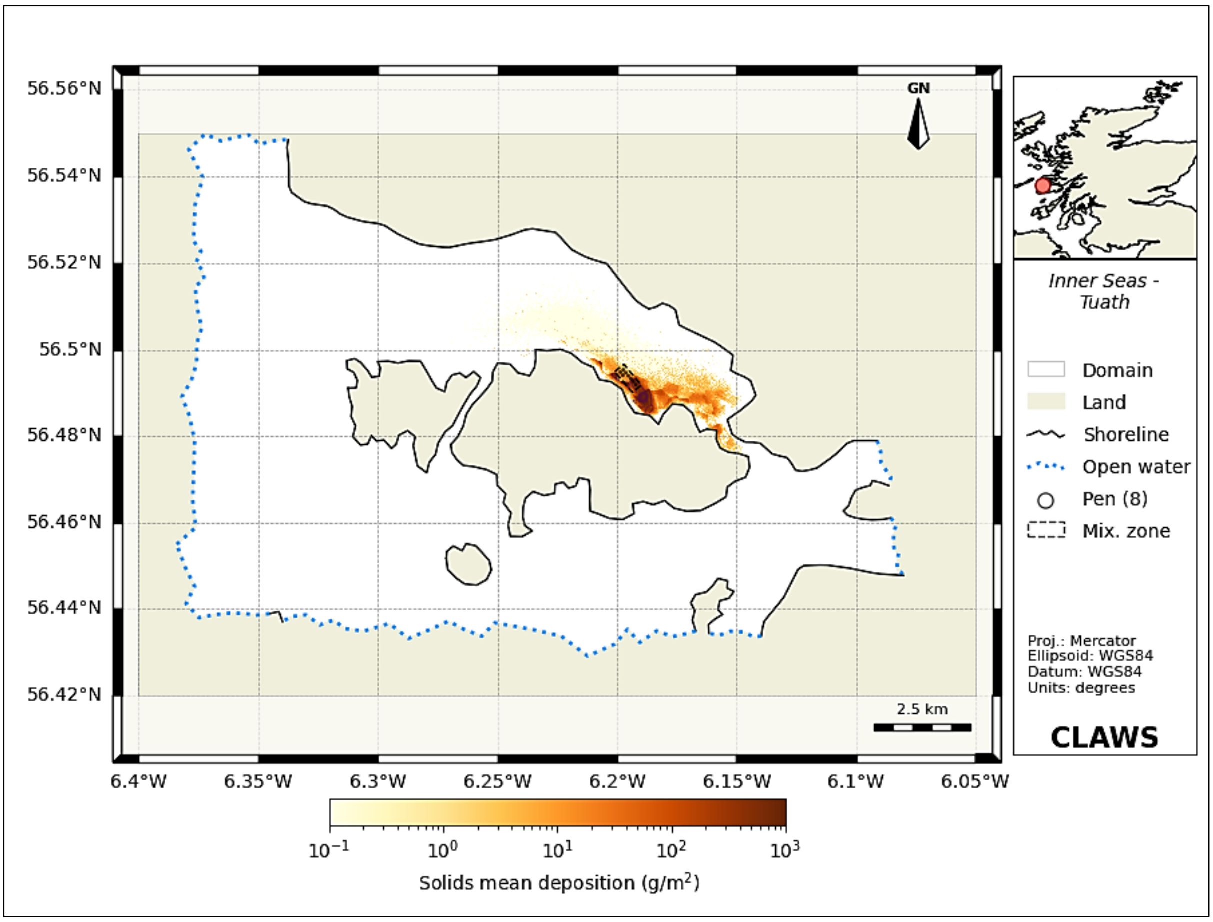

Figure 4.7 *Waste solids (feed and faeces) mean deposition footprint (g/m^2) for the existing farm at Tuath. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 850 tonnes.*

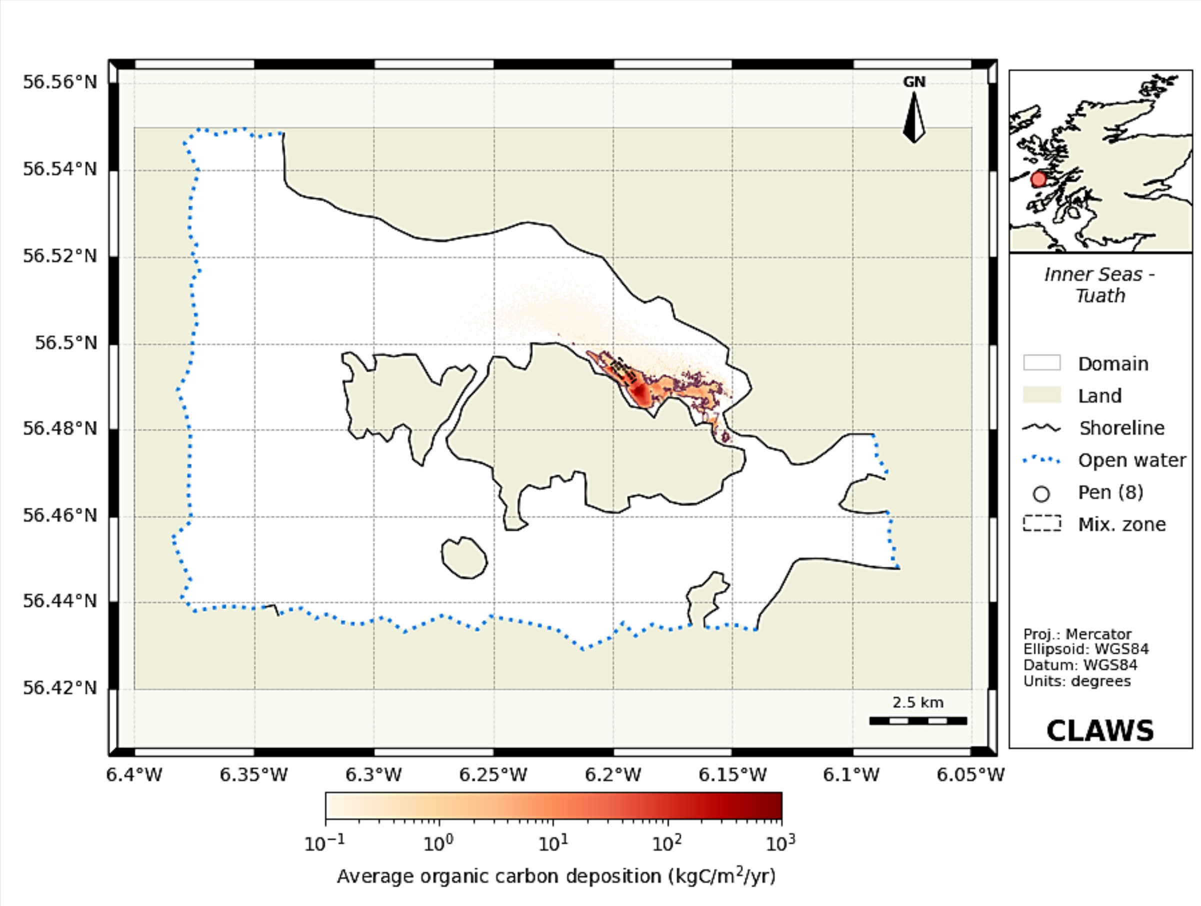

Figure 4.8 *Footprint area of particulate organic carbon (kgC/m^2/year) for the existing farm at Tuath. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. Contour shown is delimited by the value of 0.7 kgC/m^2/year. Above this critical value, it has been shown that the infaunal diversity of sediments is reduced, and the seabed can be considered 'degraded' [GILL_2002]. Area of the contour footprint is 1.68 km^2.*

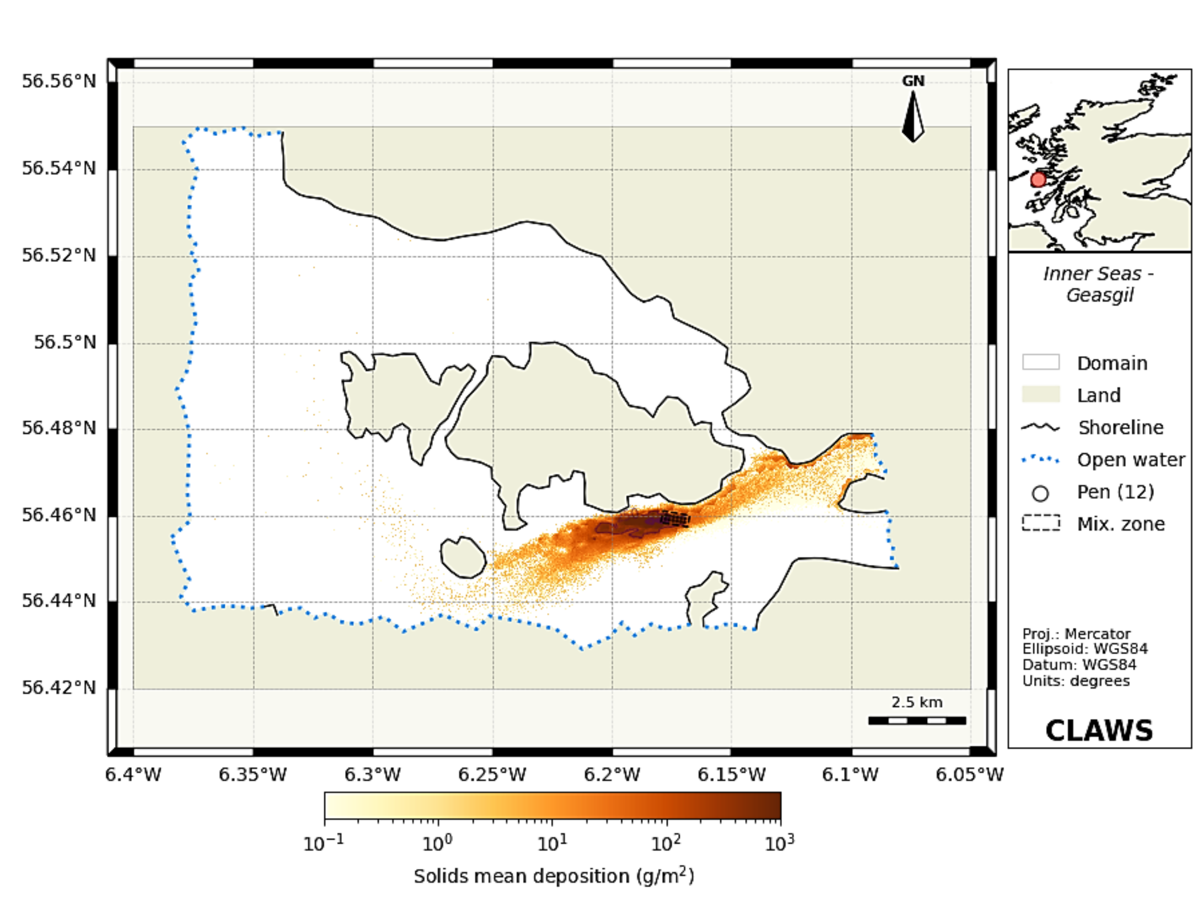

Figure 4.9 *Waste solids (feed and faeces) mean deposition footprint (g/m^2) for the existing farm at Geasgill. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 2500 tonnes.*

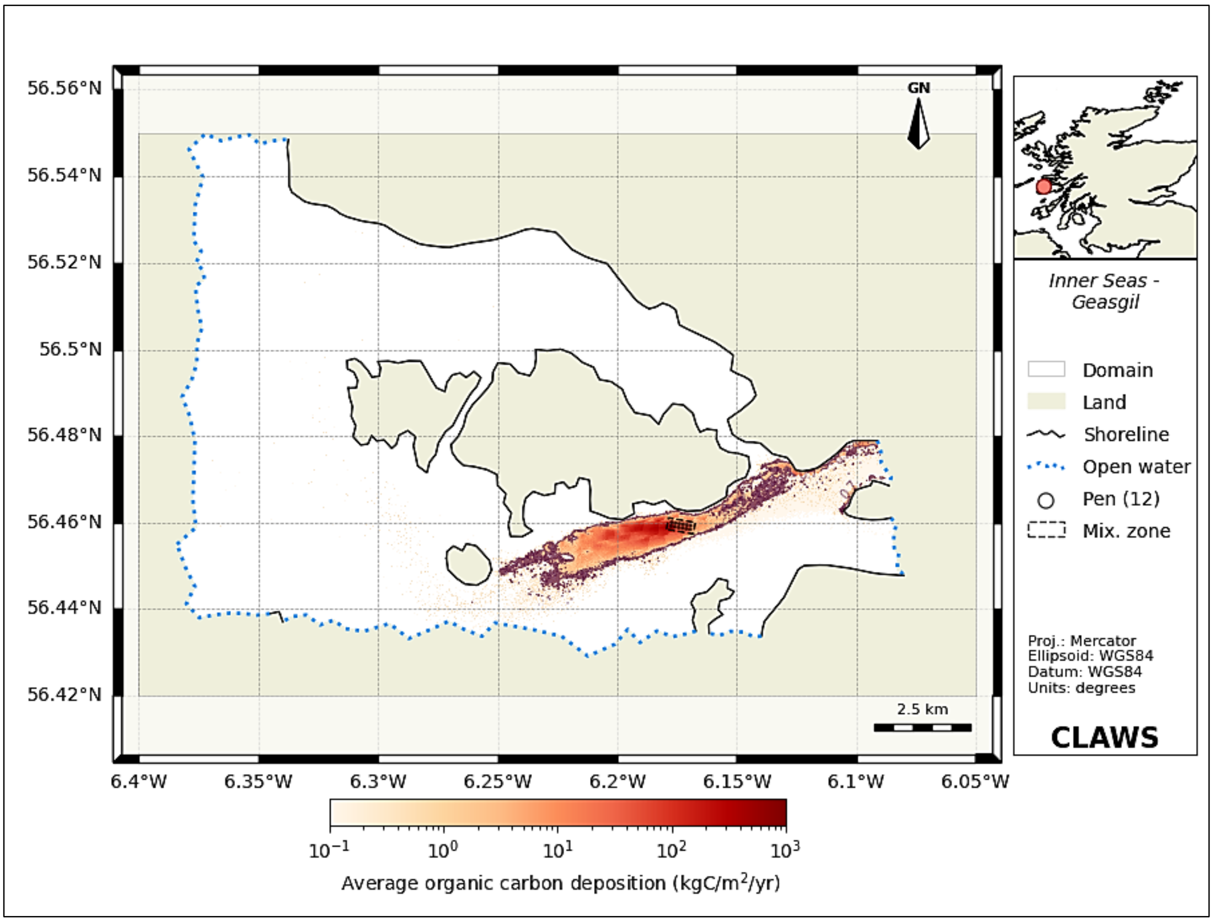

Figure 4.10 *Footprint area of particulate organic carbon (kgC/m^2/year) for the existing farm at Geasgill. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. Contour shown is delimited by the value of 0.7 kgC/m^2/year. Above this critical value, it has been shown that the infaunal diversity of sediments is reduced, and the seabed can be considered 'degraded' [GILL_2002]. Area of the contour footprint is 5.23 km^2.*

Table 4.4 *Summary of waste results for all 4 farms in the Little Colonsay system.*

	Salmon Farm			
	Little Colonsay	Gometra	Tuath	Geasgill
AZE (Mixing Zone) (m^2)	180,000	240,000	210,000	210,000
250 g/m^2 footprint area (m^2)	663,600	385,600	266,000	919,600
Ratio of footprint-to-AZE	3.69	1.61	1.27	4.38
Mean solids deposition intensity inside footprint (g/m^2)	1,414	704	1,071	850
Peak solids deposition intensity inside footprint (g/m^2)	3,915	2,506	6,186	3,393
Surface area of Inner Seas at Little Colonsay (km^2)	141.84	141.84	141.84	141.84
Organic carbon footprint area (km^2)	6.14	13.98	1.68	5.23
Ratio of carbon footprint to Inner Seas surface area (%)	4.3	9.8	1.2	3.7
Benthic Impact Index (BII) (Table 4.2)	4	4	3	4
Nutrient Equilibrium Concentration Enhancement Index (ECE) (Table 4.1)	2	2	2	2
Combined ECE+BII Index	6	6	5	6
Combined Impact Category (Table 4.3)	2	2	2	2

Analysis of the data in Table 4.4 shows that all farms in the system are likely to generate a solids waste footprint in excess of the statutory Allowable Zone of Effect (AZE) or 'mixing zone'. Values of up to 4.38 times the AZE (Geasgill) were likely to be found in the system.

The mean solids deposition intensity inside the 250 g/m^2 contour is likely to be below the SEPA threshold of 2000 g/m^2 for all farms. However, peak values within the 250 g/m^2 contour were found to be in excess of 2000 g/m^2; levels which are categorised as *"less likely to lead to an acceptable sea bed ecological outcome"* [SEPA_SCRN_2023].

The Benthic Impact Index (BII) is calculated by dividing the organic carbon footprint size by the sea loch surface area to give a percentage degradation. The BII is then added to the equilibrium concentration enhancement (ECE) index for dissolved nitrogen to produce a combined index. For all farms in the system, the combined indices produced an impact categorisation value of 2, meaning that *"…a degree of precaution should (also) be applied to consideration of further fish farming development in these areas"* [GILL_2002].

4.3 *Benthic Impact for all 4 farms combined*

The combined organic carbon footprint area impacted by waste solids deposition from all 4 farms in the system, Little Colonsay, Gometra, Tuath and Geasgill, was 27.03 km^2. This equates to a percentage sea bed degradation of 19.1 % and a BII of 5 (Table 4.2). The combined BII and ECE index equals 7, implying that the combined effects of all 4 farms in the system will be likely to produce a Category 1 rating (Table 4.3). In these areas "*…the most precautious approach to further fish farming development should be adopted.*" [GILL_2002].

Finally, Appendix A shows other output from the waste study which highlight the range of results that are possible from the CLAWS software suite for waste analysis.

5. Comments and conclusions

A particle-based waste model has been developed for application in salmon farms in semi-enclosed sea lochs and open sea areas. The waste model is part of a suite of particle-based, open-source modules known as CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS_2023]. Other particle-based modules in the CLAWS repository include those to describe dissolved nutrients, bath treatments and parasitic sea lice from salmon farms. The waste model predicts the particulate waste dispersion in the marine environment and comparison is made against the statutory SEPA standards for the Allowable Zone of Effect (AZE) and Benthic Impact Index (BII). A 2D, depth-averaged hydrodynamics model based on the Telemac code has been used to drive the particle-based waste dispersion calculation and the hydrodynamics model contains the influence of meteorological forcing. For the Lagrangian particle-tracking the open-source code OpenDrift [OpenDrift_2023] has been used. Results demonstrate the ability the CLAWS waste code to successfully predict waste feed and faeces impact on the sea floor and present the concentrations in a format suitable for scientific reporting. All farms in the Little Colonsay system are likely to form a sea bed footprint that is in excess of the SEPA statutory AZE. Peak concentrations of solid waste on the sea bed are likely to be in excess of the SEPA-recommended value of 2000 g/m^2. Finally, the amount of organic carbon deposition for the combined farms in the Little Colonsay system is likely to lead to a significant degradation of the sea floor. The combined ECE and BII index predicts that the system will be "Category 1" and it is advised that "*…the most precautious approach to further fish farming development should be adopted.*" [GILL_2002].

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APPENDIX A

Additional results from CLAWS waste model output:

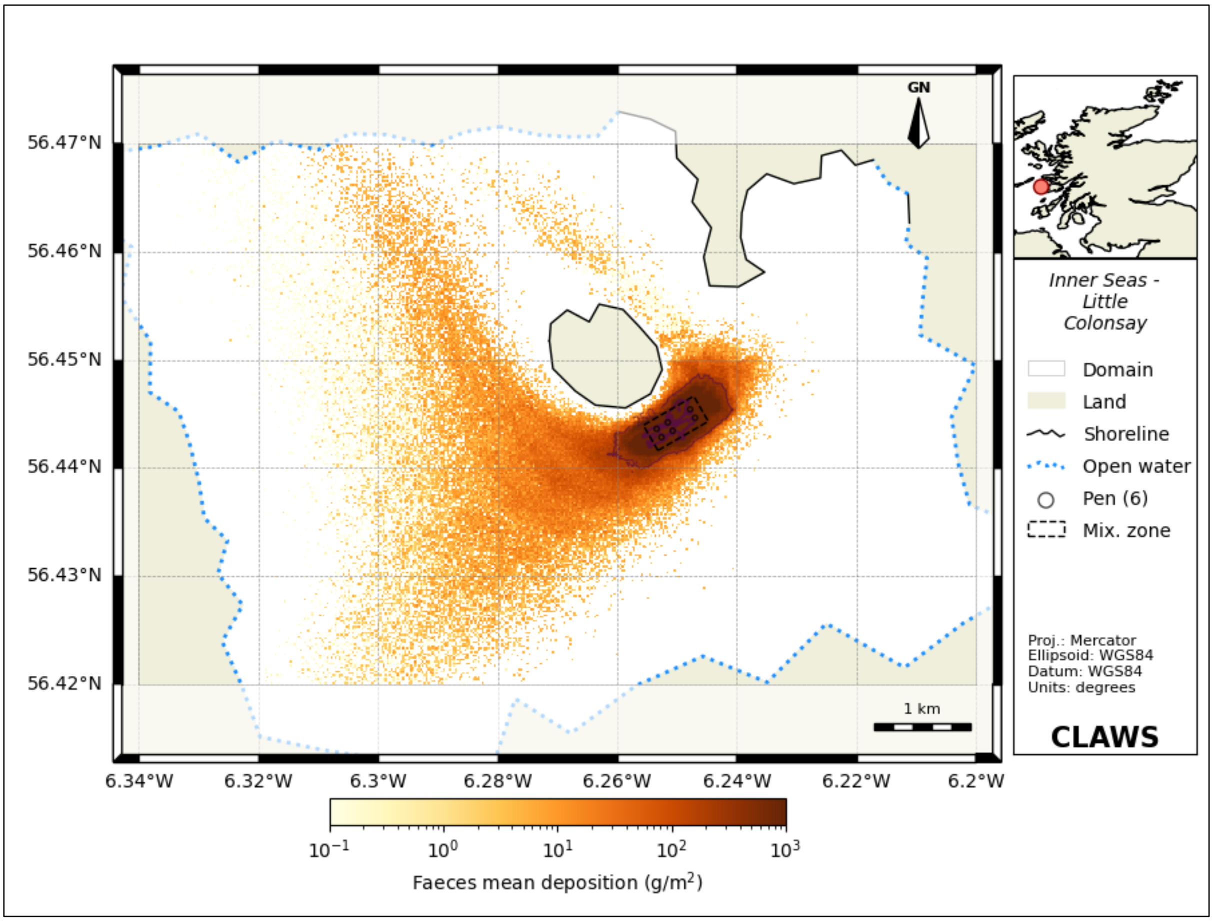

Figure A.1 *Faeces mean deposition footprint (g/m^2) for the proposed Bakkafrost farm at Little Colonsay. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 2773 tonnes.*

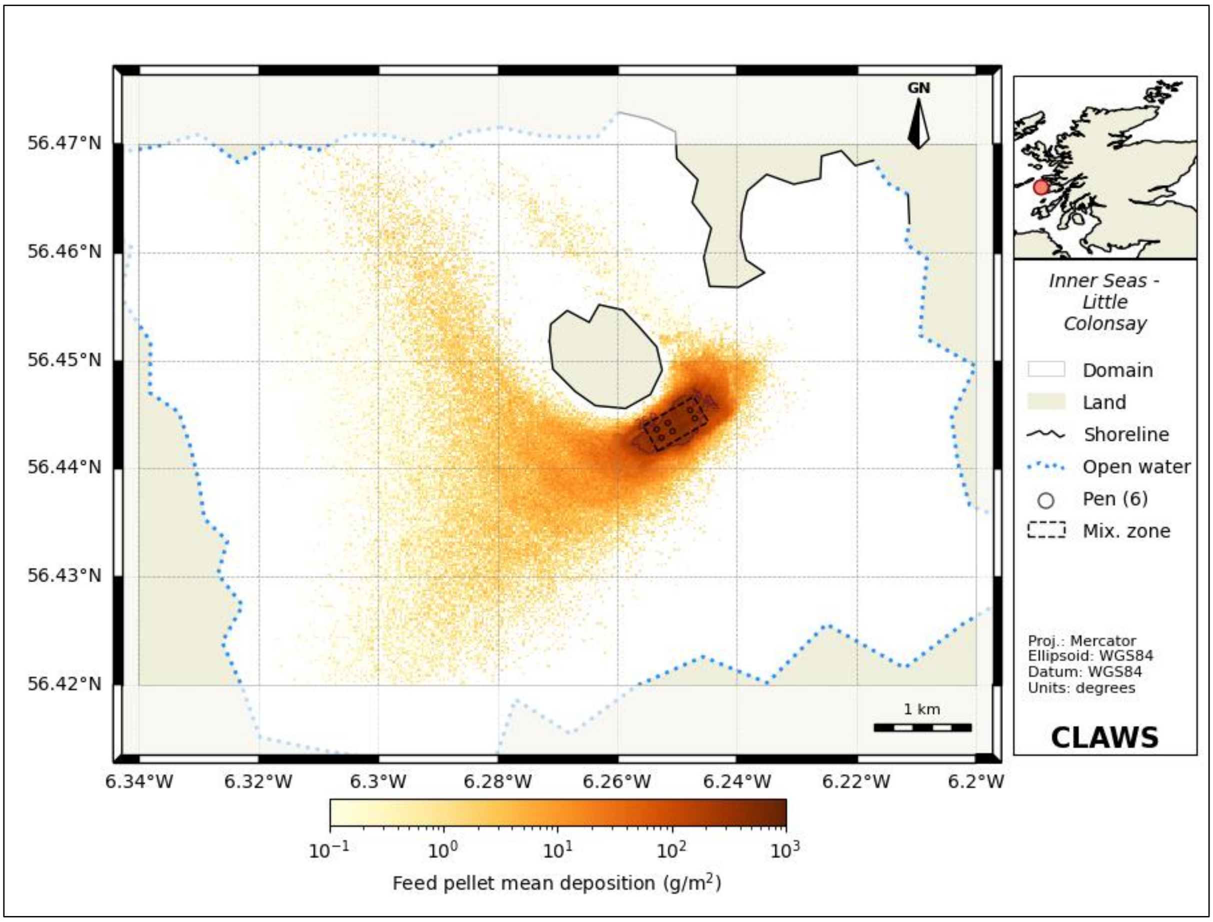

Figure A.2 *Uneaten feed pellet mean deposition footprint (g/m^2) for the proposed Bakkafrost farm at Little Colonsay. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 2773 tonnes.*

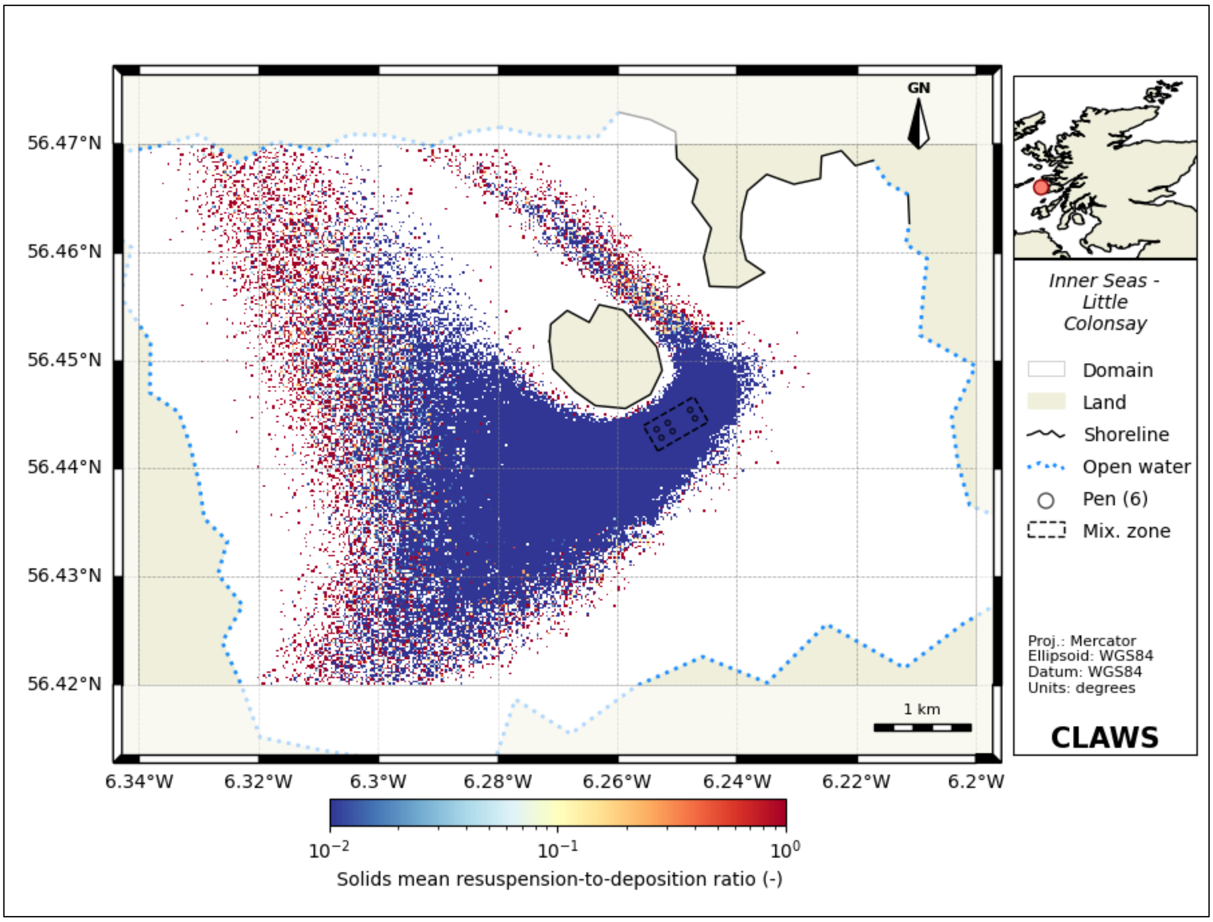

Figure A.3 *Solids (feed and faeces) mean resuspension-to-deposition ratio for the proposed Bakkafrost farm at Little Colonsay. Values correspond to the average over 90-days from 1st March - 31st May 2019. Values in red indicate areas where the critical shear rate is exceeded and a particle is likely to undergo resuspension.*

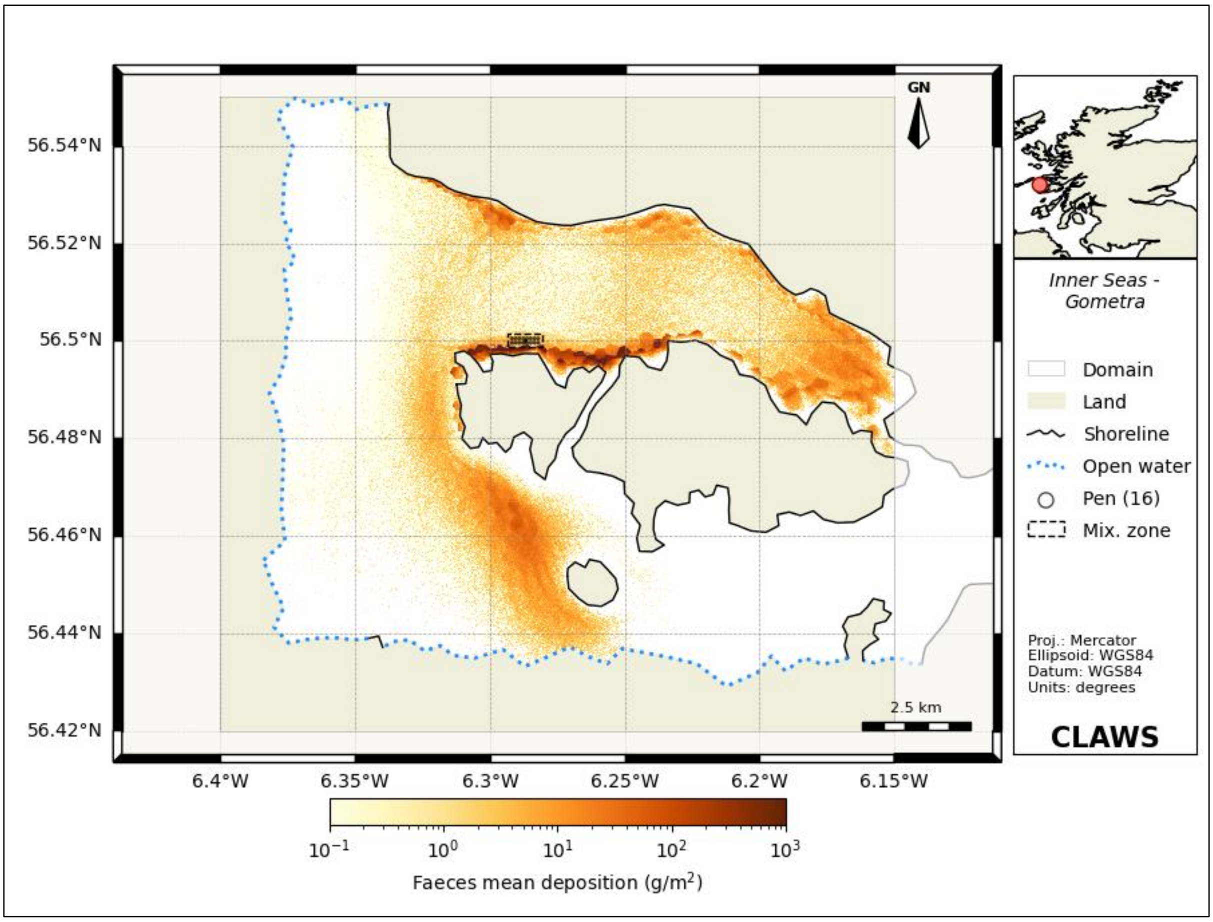

Figure A.4 *Faeces mean deposition footprint (g/m^2) for the existing farm at Gometra. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 1944 tonnes.*

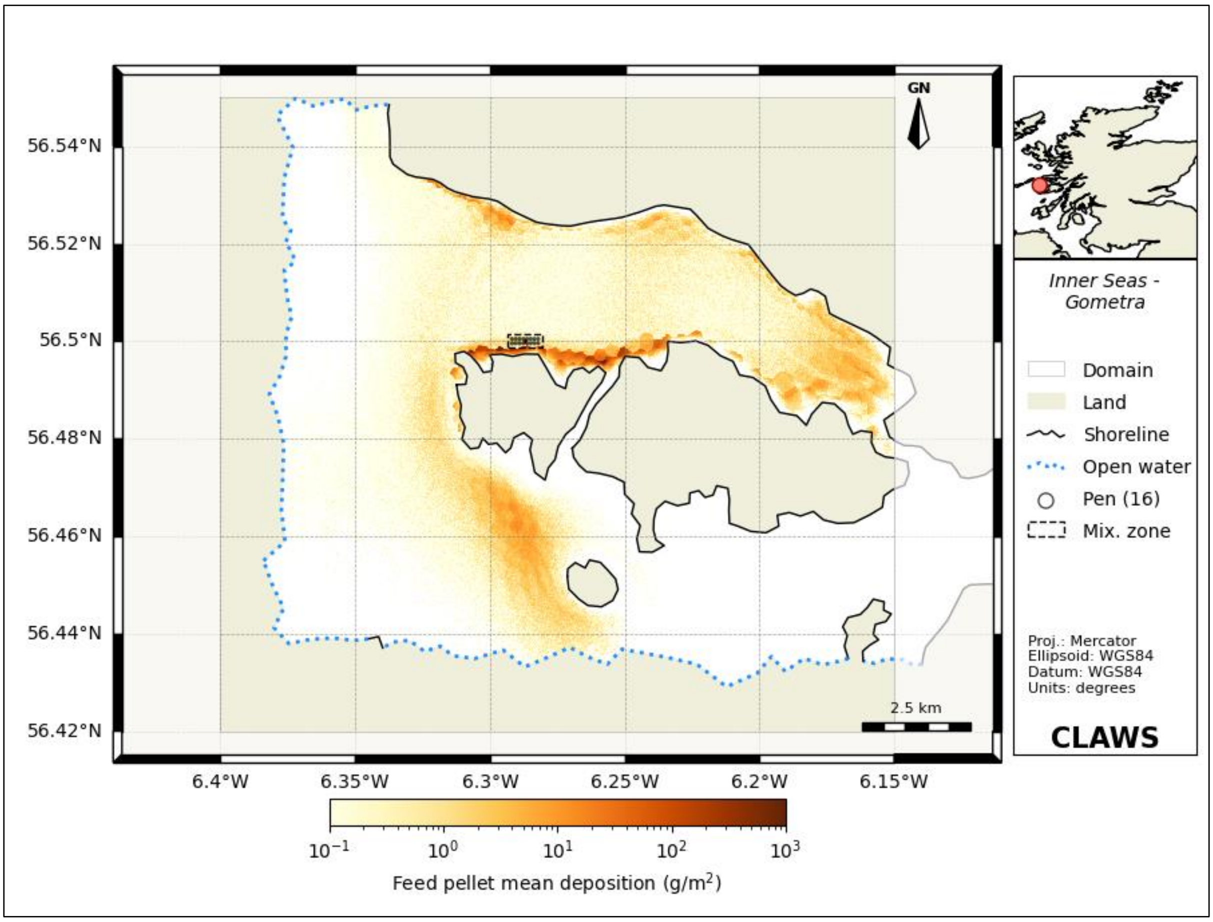

Figure A.5 *Uneaten feed pellet mean deposition footprint (g/m^2) for the existing farm at Gometra. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 1944 tonnes.*

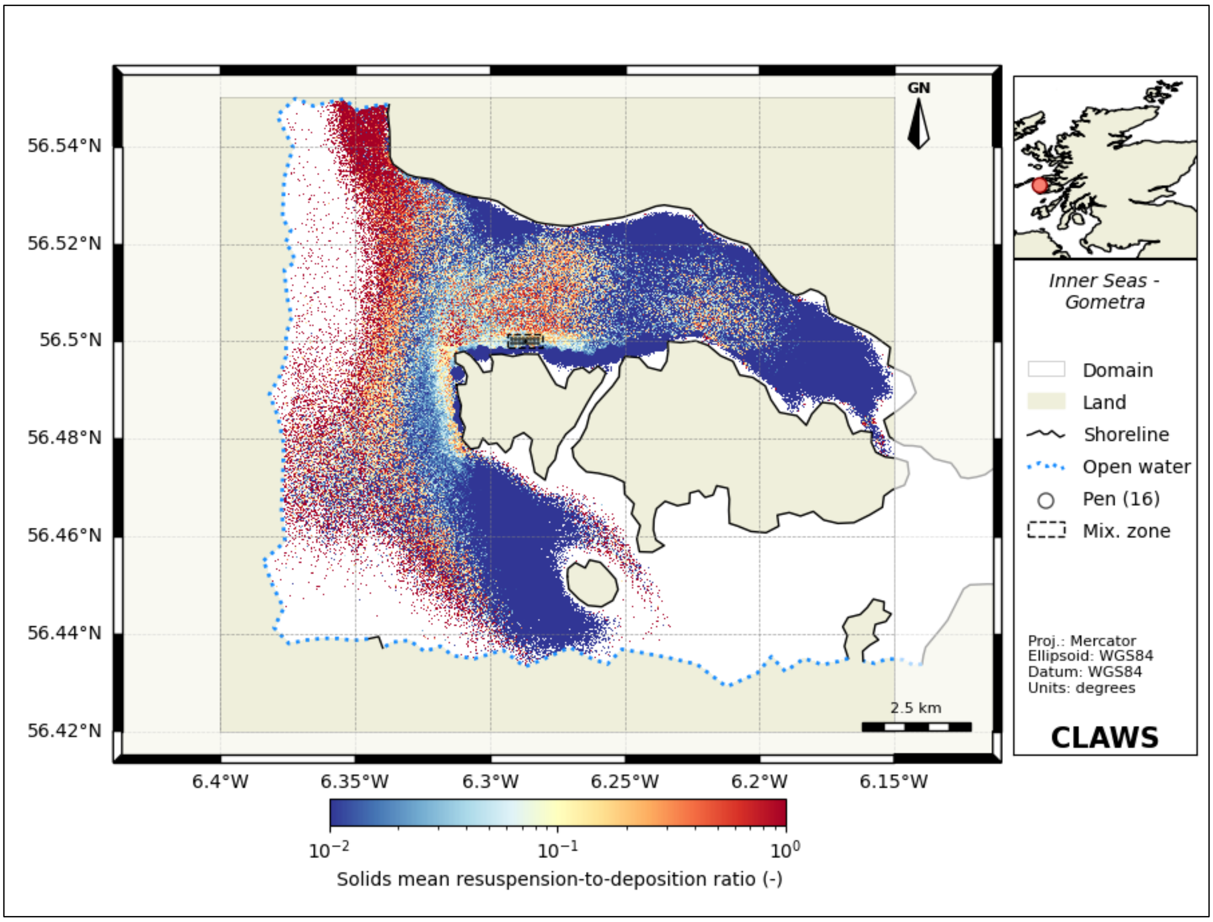

Figure A.6 *Solids (feed and faeces) mean resuspension-to-deposition ratio for the existing farm at Gometra. Values correspond to the average over 90-days from 1st March - 31st May 2019. Values in red indicate areas where the critical shear rate is exceeded and a particle is likely to undergo resuspension.*

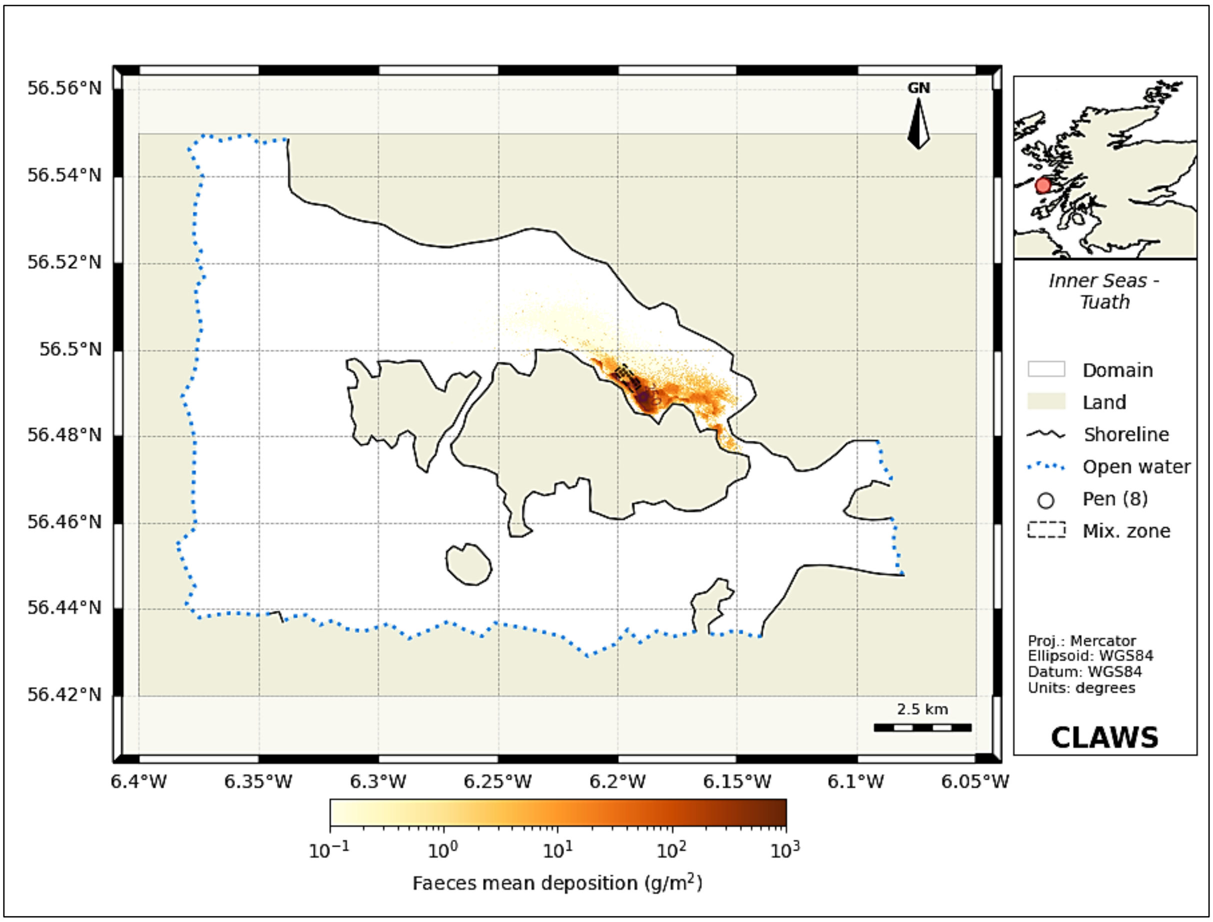

Figure A.7 *Faeces mean deposition footprint (g/m^2) for the existing farm at Tuath. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 850 tonnes.*

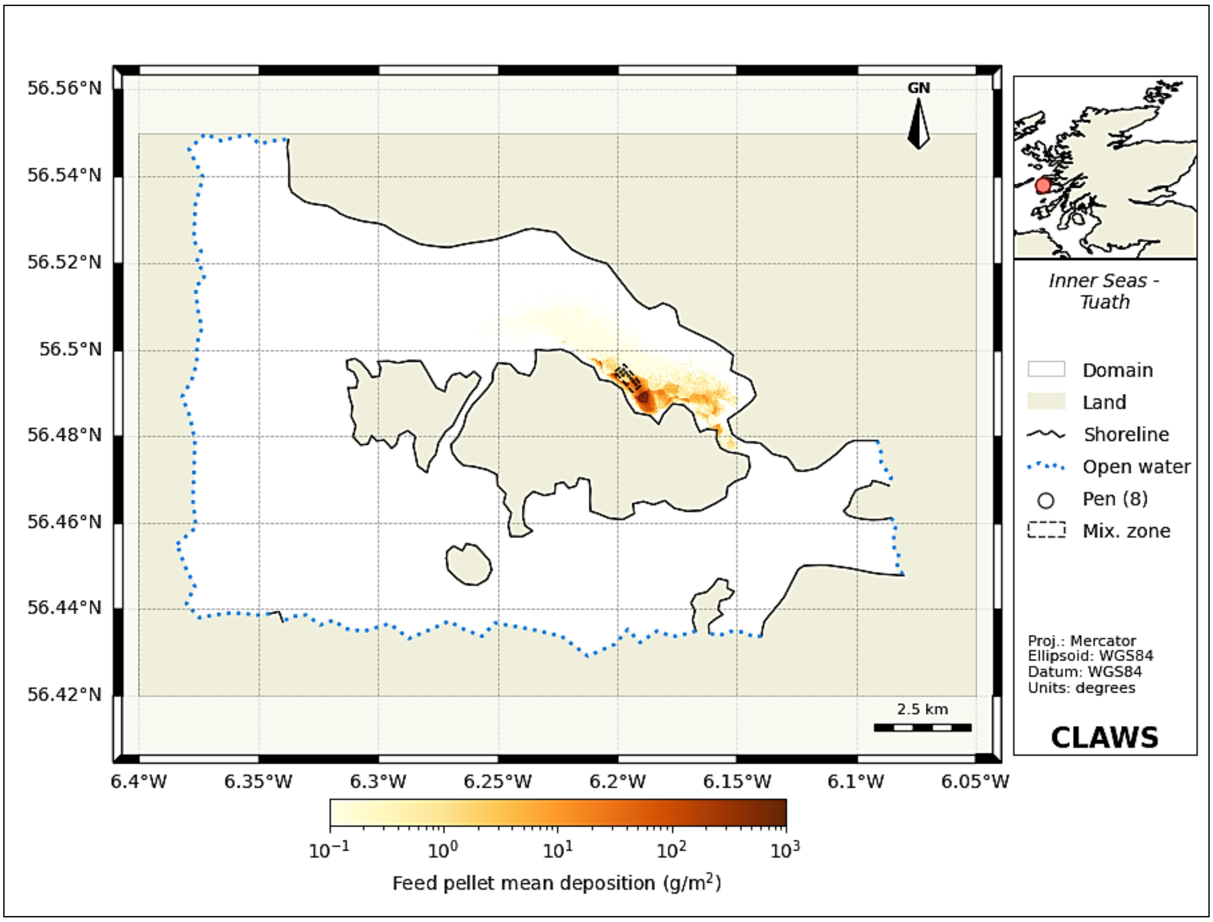

Figure A.8 *Uneaten feed pellet mean deposition footprint (g/m^2) for the existing farm at Tuath. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 850 tonnes.*

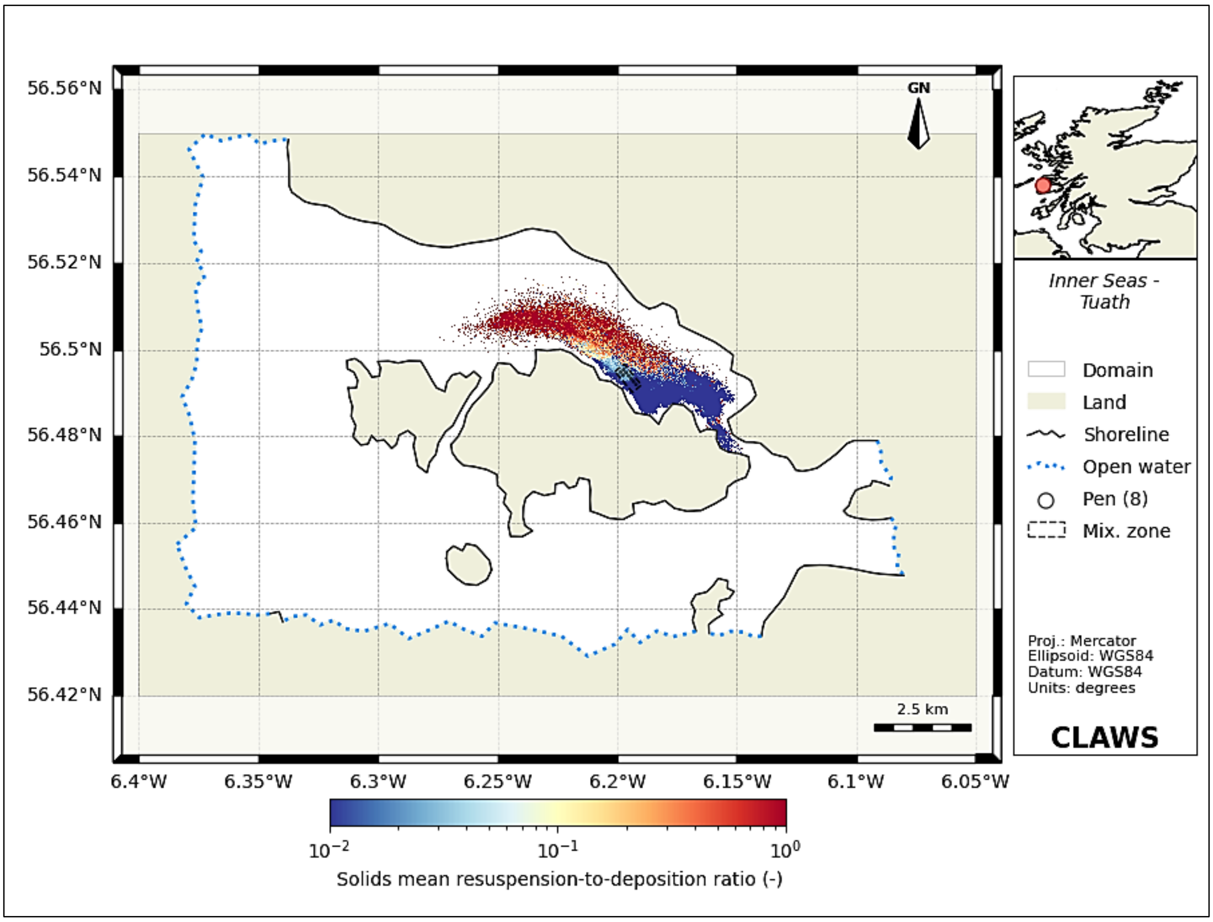

Figure A.9 *Solids (feed and faeces) mean resuspension-to-deposition ratio for the existing farm at Tuath. Values correspond to the average over 90-days from 1st March - 31st May 2019. Values in red indicate areas where the critical shear rate is exceeded and a particle is likely to undergo resuspension.*

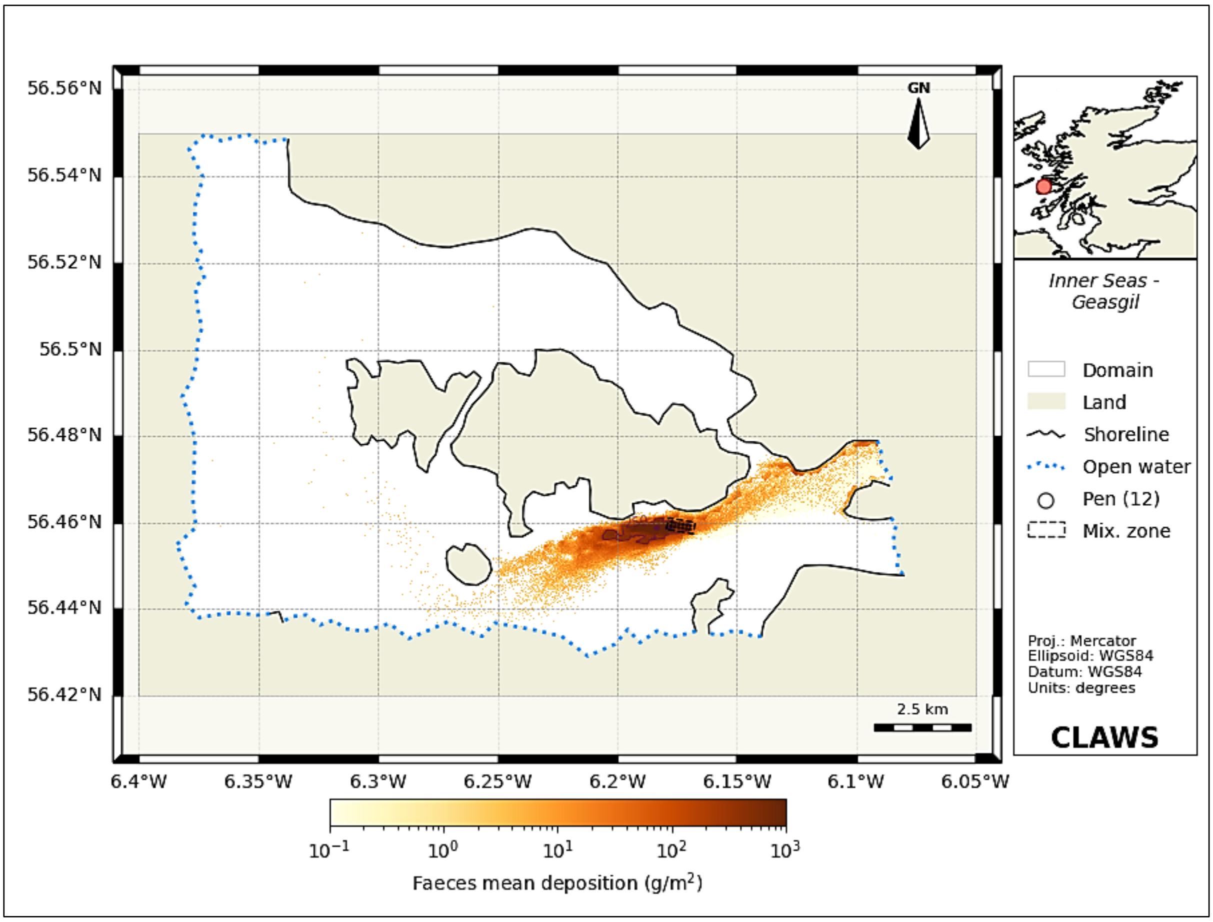

Figure A.10 *Faeces mean deposition footprint (g/m^2) for the existing farm at Geasgill. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 2500 tonnes.*

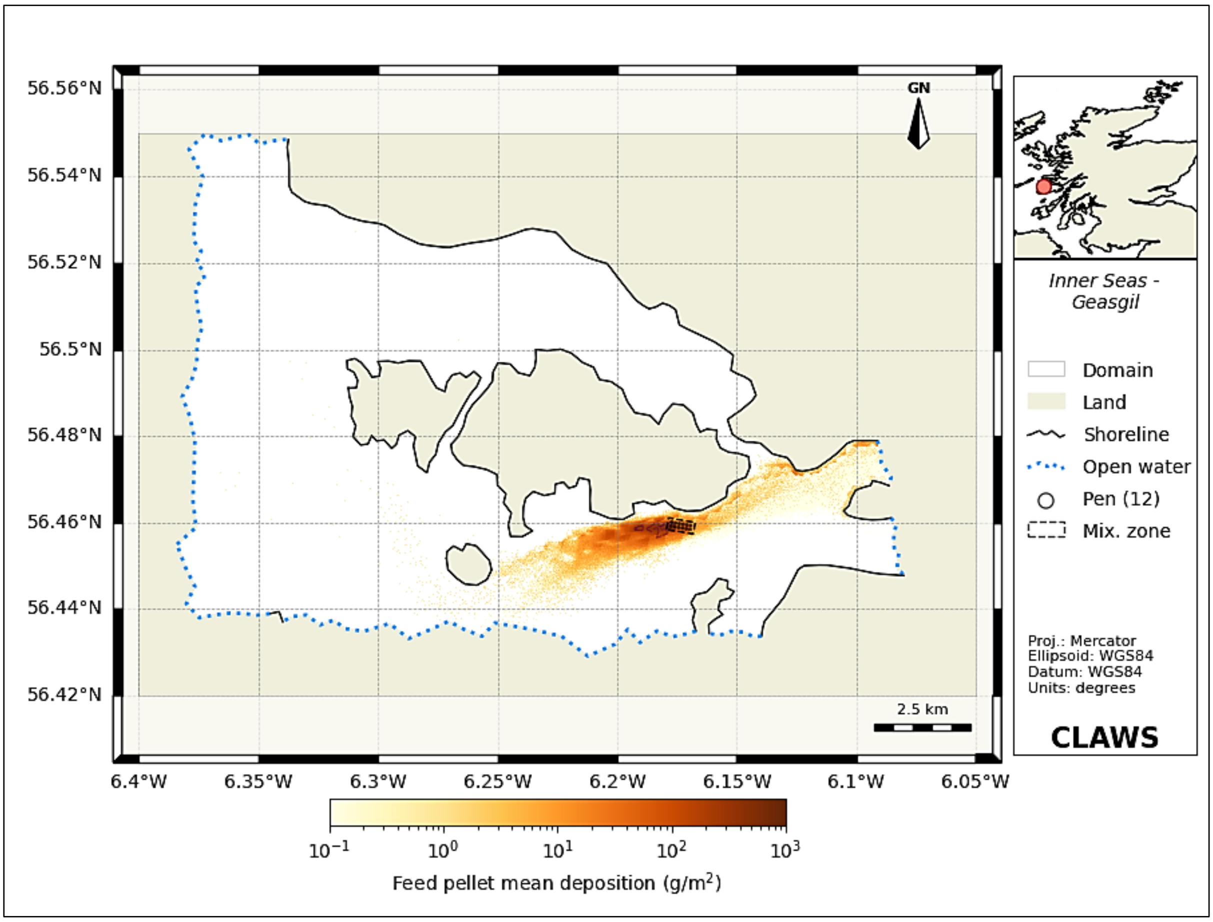

Figure A.11 *Uneaten feed pellet mean deposition footprint (g/m^2) for the existing farm at Geasgill. Values correspond to the average sea bed deposition over 90-days from 1st March - 31st May 2019. The farm biomass was 2500 tonnes.*

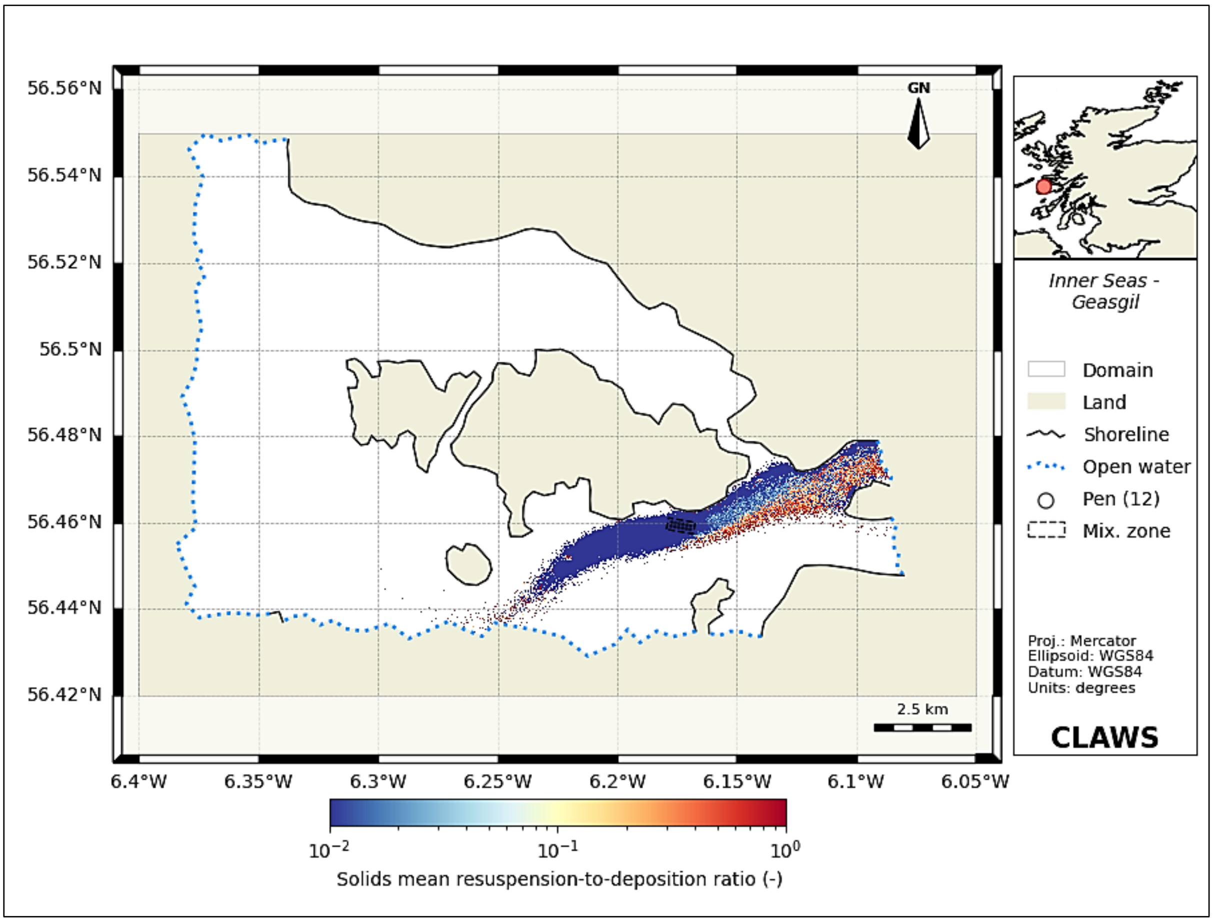

Figure A.12 *Solids (feed and faeces) mean resuspension-to-deposition ratio for the existing farm at Geasgill. Values correspond to the average over 90-days from 1st March - 31st May 2019. Values in red indicate areas where the critical shear rate is exceeded and a particle is likely to undergo resuspension.*