Hydrodynamic and Medicine Dispersion Modelling at Ardgour (Linnhe) Fish Farm Site

METHOD STATEMENT

Mowi Scotland Limited

November 2022

[redacted]

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1 INTRODUCTION

This method statement presents the specifications and rationale for the use of computer modelling to predict potential environmental effects of the existing Mowi Scotland fish farm site at **Ardgour (Linnhe)**. The models to be used include:

(i) a hydrodynamic (HD) model (WeStCOMS 2) coupled with the particle-tracking model UnPTRACK to simulate the discharge, dispersion and fate of residues of bath medicines.

The purpose of the modelling is to adequately represent the coastal processes involved in particle transport in the near field and far field, and to inform and support the resulting CAR application. This method statement outlines the methodology that will be used at Ardgour (Linnhe) in order to apply for an increased azamethiphos consent for the cage farm site that meets regulatory requirements and is in balance with the surrounding marine environment.

The modelling report will briefly describe the following aspects of the modelling process:

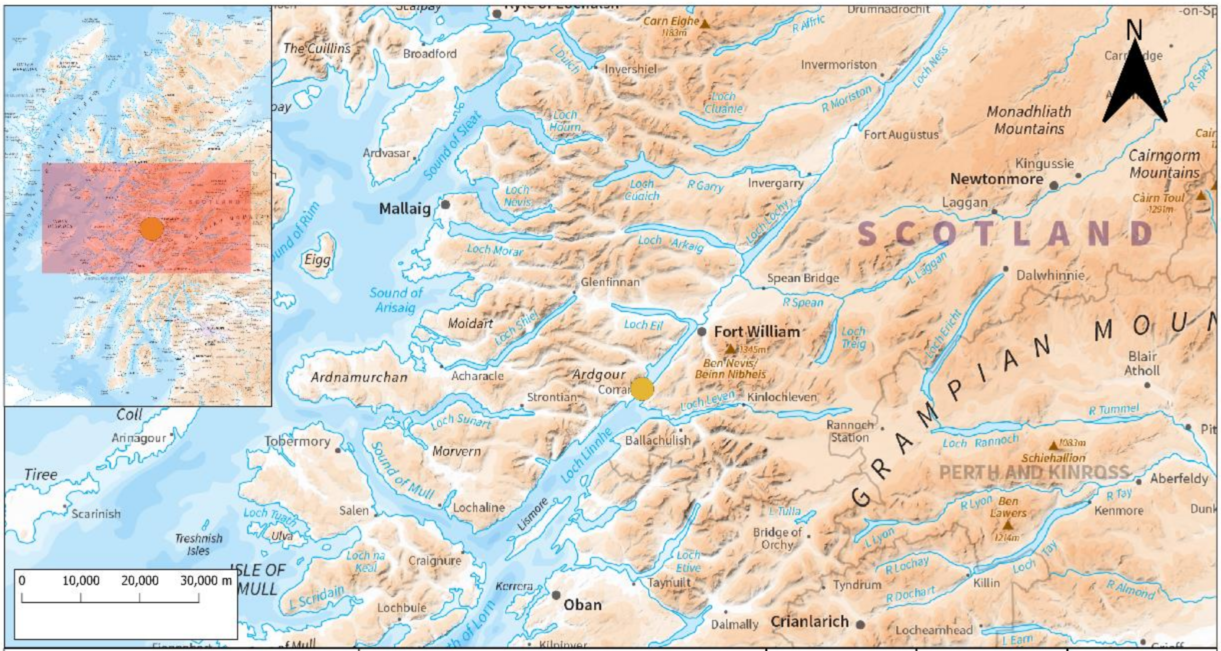
- Hydrodynamic modelling; choice of model; configuration; boundary conditions; model data comparison;
- Bath modelling using a particle-tracking approach;
- Data collection, current data collection.

2 SITE

The existing site layout at Ardgour (Linnhe) consists of ten circular pens of 120m circumference (*Figure 1* and *Figure 2*) with a maximum biomass of 2500 T. The pens are in a 2 x 5 formation, held in a 75 m grid with 15 m deep nets.

Table 1. Details of the proposed application at Ardgour (Linnhe)

SITE DETAILS	
Site Name:	Ardgour (Linnhe)
Site location:	Loch Linnhe
Peak biomass (T):	2,500
Proposed feed load (T/yr):	6387.5
Proposed treatment use:	Azamethiphos
CAGE DETAILS	
Group location:	NN01456455
Number of cages:	10
Cage dimensions:	120m circumference
Grid matrix (m)	75
Working Depth (m):	15
Cage group configuration:	2 x 5
Cage group distance to shore (km):	0.301



ARDGOUR (LINNHE) FISH FARM	Legend	1:500000	2021-11-22	[redacted]
MAP OF SITE LOCATION	Ardgrour (Linnhe) outer site centroid			
Overview map for location of Ardgrour (Linnhe)		Scale	Date	Drawn

Figure 1. Ardgour (Linnhe) site location (●) NorthWest of Corran narrows.

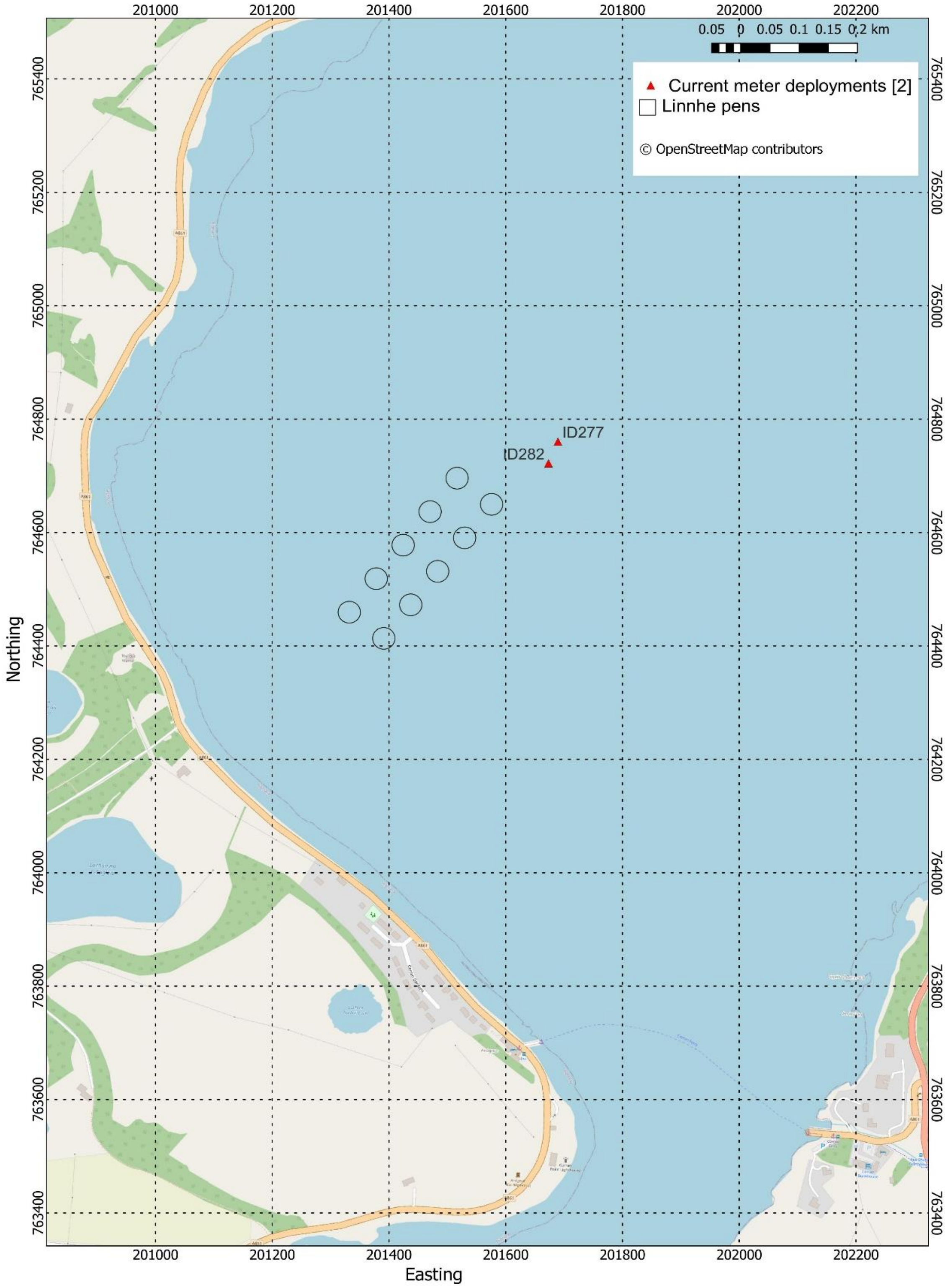


Figure 2. The existing 10 x 120m cages (O) at Ardgour (Linnhe). The current meter locations (▲) are indicated.

3 SCOPE OF MODELLING - KEY ISSUES TO BE ADDRESSED

The proposed modelling is designed to simulate the release, dispersion and fate of azamethiphos from the pens to the area around the pens, and to determine subsequent dispersion over a larger domain.

Two models will be described in this statement: the hydrodynamic (HD) model, a particle-tracking model, UnPTRACK, used to simulate the dispersion of bath medicines. The hydrodynamic model will initially be used to determine the maximum distance that particles released from the farm site will travel in all directions. This will dictate the size and shape of the study model domain for the bath medicine model. Current velocity fields will then be extracted from the hydrodynamic model and used to provide input data to the particle tracking model UnPTRACK, which will then be run to produce outputs of topical sea lice treatment concentrations.

The use of a calibrated hydrodynamic model to provide spatially-varying current data provides more realistic input data to the particle tracking model, UnPTRACK, compared to the use of a single current dataset from a fixed-location current meter, reproducing the changing flow fields in response to the topography and bathymetry of the regional domain.

Outputs from the particle tracking models will be used to make an application to SEPA for the site.

3.1 General Environmental Risks Associated with Aquaculture Discharges

The main components of the discharges from marine pen fish farms are associated with the discharge of particulate wastes, anti-parasitic medicine residues and dissolved nutrients. This report only concerns topical sea lice medicines.

<u>Medicine Residues</u>

Medicinal sea lice treatments may be carried out in one of two ways at Ardgour (Linnhe):

- Bath treatments *in-situ* by enclosing the pen in question fully with a large tarpaulin. The net is lifted to gently crowd the fish together in the smallest safe volume. The tarpaulin is passed underneath the net and pulled up around the pen above the water level. When the fish are totally enclosed in the tarpaulin, treatment can begin. Oxygenation equipment is used to ensure the water is well oxygenated and prevent the fish from experiencing stressful suboptimal oxygen levels. Once the treatment is completed the tarpaulin is removed and the nets lowered to uncrowd the fish.

- Fish may be treated in tanks on board specialist wellboats. Following treatment, the dislodged lice are collected and disposed of, then the treatment water is discharged into the sea.

The regulatory approach to use of authorised medicinal substances is based on the use of predictive models to set limitations on the quantities and rate of release of these compounds to meet the relevant Environmental Quality Standards (EQS) outside a defined mixing zone (previously referred to as an allowable zone of effect or AZE), based on the hydrographic characteristics of each site. The purpose of the mixing zone is to allow an effective dose of medicine to be administered within a pen, but to ensure that the dose results in lower concentrations than those that affect the most vulnerable fauna beyond the mixing zone.

3.1 Consented volumes of medicines are regulated by site-specific numeric modelling using inputs of hydrographic, bathymetric, geographic, and farm equipment infrastructure. Release and dispersion of medicine residues is predicted and simulated environmental concentrations are compared to the appropriate Environmental Quality Standard for each medicine. The volumes of medicines consented are tailored to the hydrodynamics and bathymetry of the site and are determined such that the set EQS for each compound would not be breached outside the mixing zone.

4 HYDRODYNAMIC MODEL DESCRIPTION AND CONFIGURATION

The hydrodynamic model used was WeStCOMS (Aleynik et al., 2016), an implementation on the Scottish West Coast of FVCOM (Finite Volume Community Ocean Model), 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 equations describing the evolution and conservation of momentum, temperature, salinity and turbulence parameters, the latter using a turbulence closure submodel. The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is presented using generalized terrain-following coordinates. The General Ocean Turbulent Model (GOTM) developed by Burchard's research group in Germany (Burchard, 2002) has been added to FVCOM to provide optional vertical turbulent closure schemes. FVCOM is solved numerically by a second-order accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. This approach combines the best features of finite-element methods (grid flexibility) and finite-difference methods (numerical efficiency and code simplicity) and provides a much better numerical representation of both local and global momentum, mass, salt, heat, and tracer conservation. The ability of FVCOM to accurately solve scalar conservation equations in addition to the topological flexibility provided by unstructured meshes and the simplicity of the coding structure has made FVCOM ideally suited for many coastal and interdisciplinary scientific applications, such as typically found in Scotland. The mesh flexibility allows greater spatial resolution in near-shore areas without excessive computational demand.

The model is forced by a tidal condition along the open boundary, and by frictional stresses at the surface and seabed. At the seabed, the frictional stress, $\boldsymbol{\tau}_b$, is calculated using a quadratic equation where:

$$\tau_b = \rho C_D \boldsymbol{U}|\boldsymbol{U}| \tag{1}$$

where ρ = 1025 kg m^{-3} is the water density, **U** is the velocity in the layer closest to the seabed. The drag coefficient, C_D, is calculated from the bed roughness lengthscale, z_0, using:

$$C_D = \left(\frac{\kappa}{\ln\left(\frac{z_b+z_0}{z_0}\right)}\right)^2 \tag{2}$$

where κ=0.4 is von Karman's constant, and z_b is the height above the bed of the lowest velocity point. The value of z_0 was varied during calibration to provide the best fit to observations of sea level and velocity.

Wind forcing is applied as a surface stress calculated from hourly wind speed and direction. Wind stress is calculated from the wind velocity by a standard quadratic relation:

$$\tau_x = \rho_a C_S u W \tag{3a}$$
$$\tau_y = \rho_a C_S v W \tag{3b}$$

where (u,v) are the East and North components of wind velocity respectively, W is the wind speed ($W = [u^2+v^2]^{½}$), ρ_a is the density of air, and the surface drag coefficient C_S is calculated following Large and Pond (1981).

4.1 Model Configuration

The WeStCOMS unstructured mesh to be used in the marine modelling is shown in *Figure 3*. The model resolution around the Mowi site at Ardgour (Linnhe) is shown in *Figure 4*. The node spacing of the model mesh goes down to less than 50 m inshore waters near the farm pens to 3 km along the open boundary.

The hydrodynamic mesh resolution in the immediate area of the farm is similar to meshes previously used in Azamethiphos dispersion applications. It is worth noting that azamethiphos concentrations are not calculated on this unstructured mesh; instead, concentrations are calculated on a regular square grid with a finer resolution of 25 m x 25 m cells, giving detailed concentration fields. The post-processing of the 3-hour individual pen release simulations in UnPTRACK uses a still finer gridded regular grid of 10 m x 10 m.

The WeStCOMS model was upgraded to version 2 in 2019, the model consists of 99,999 nodes and 177,326 triangular elements. The WeStCOMS2 model was run in 3D mode with 11 terrain following sigma-coordinate layers, with concentration of levels in the upper part of the water column. The model bathymetry used was from WeStCOMS2 which is based on gridded SeaZone digital atlas data, Admiralty charts and a number of past and recent multibeam surveys.

WeStCOMS 2 open lateral boundaries are forced with output from a relatively high resolution (2 km) North-East Atlantic ROMS operational model, provided by the Marine Institute, Ireland. 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).

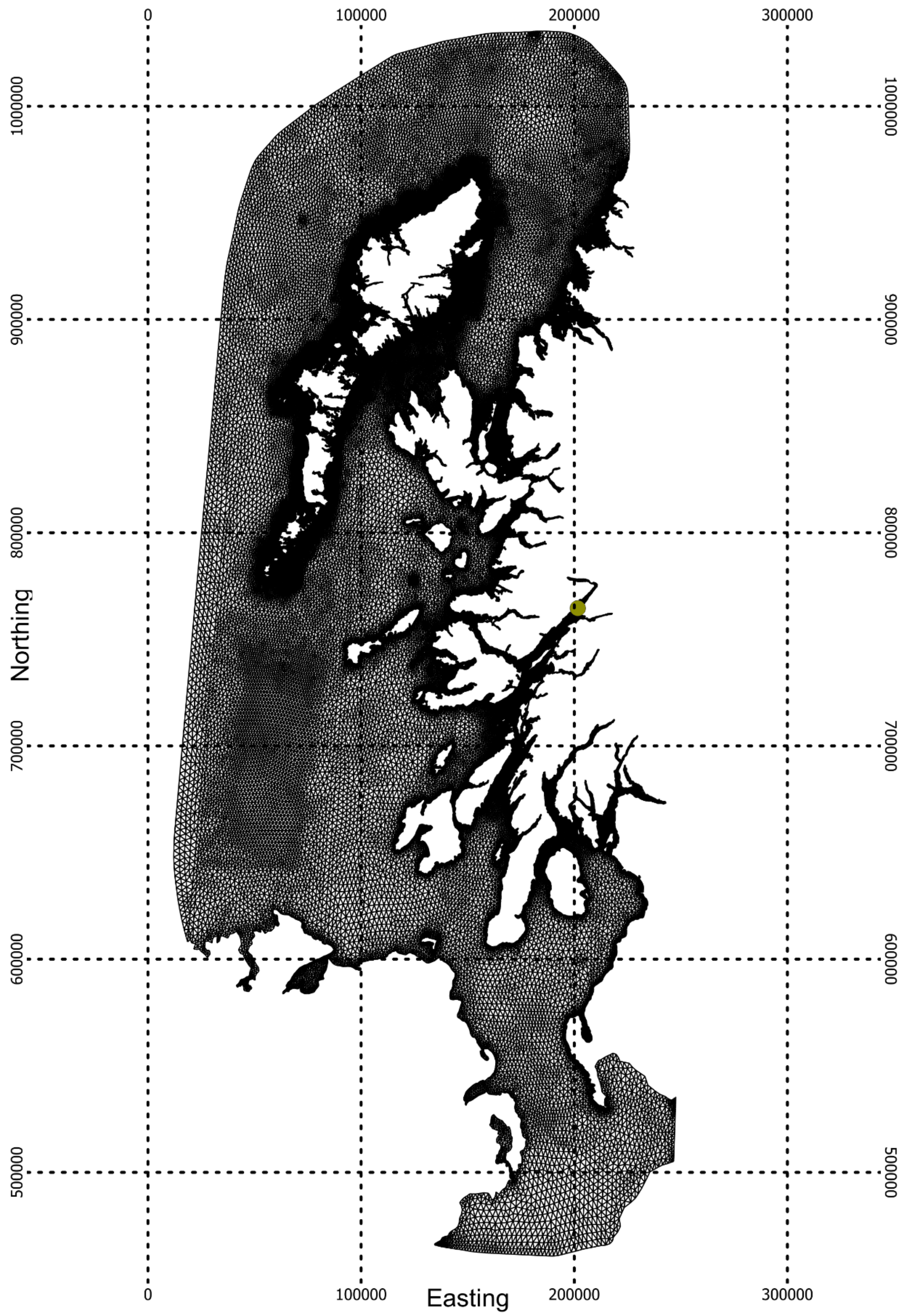


Figure 3. The WeStCOMS 2 mesh and domain. The location of Ardgour (Linnhe) (●).

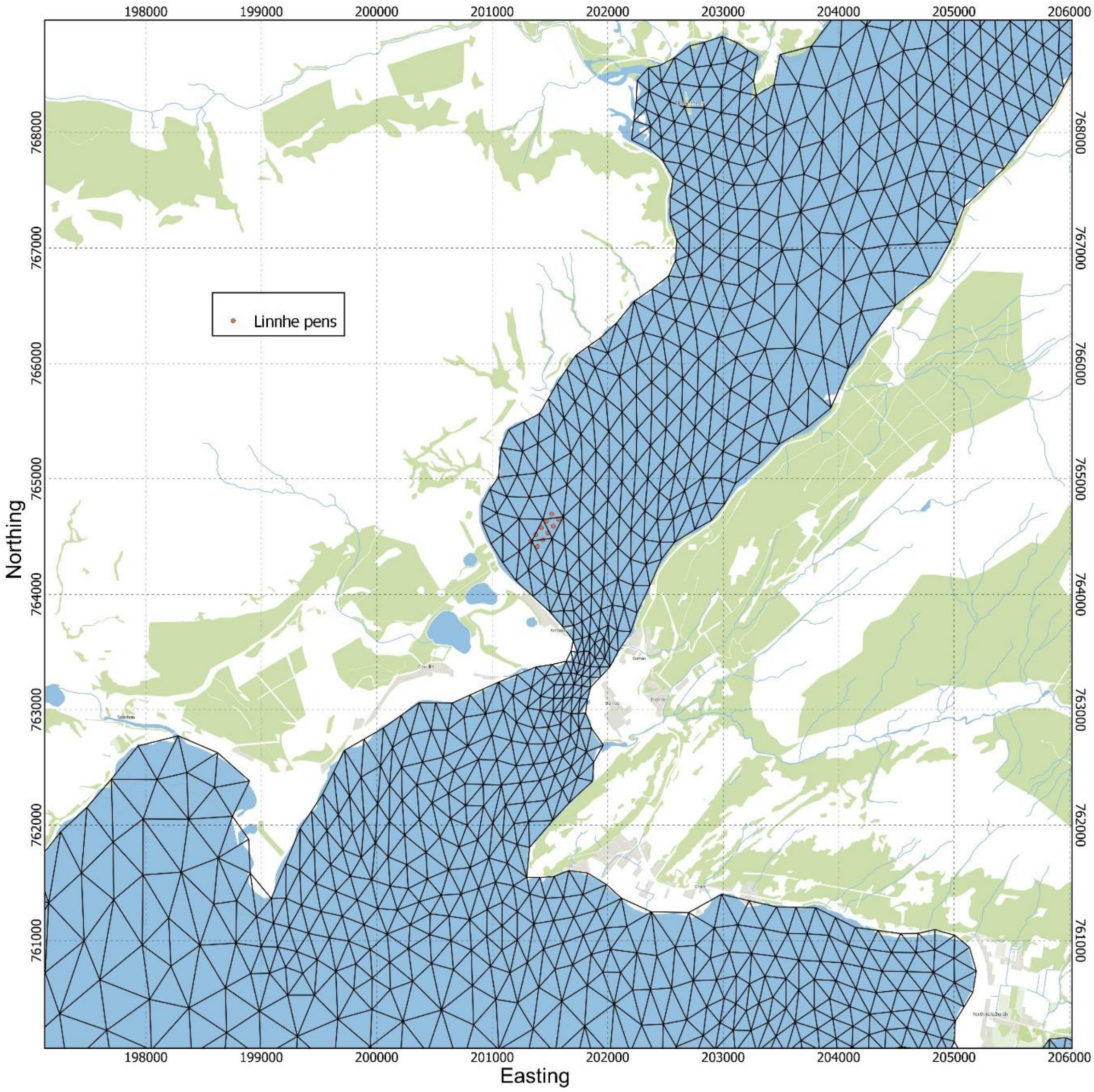


Figure 4. The unstructured mesh around the Ardgour (Linnhe) site with the existing pen locations.

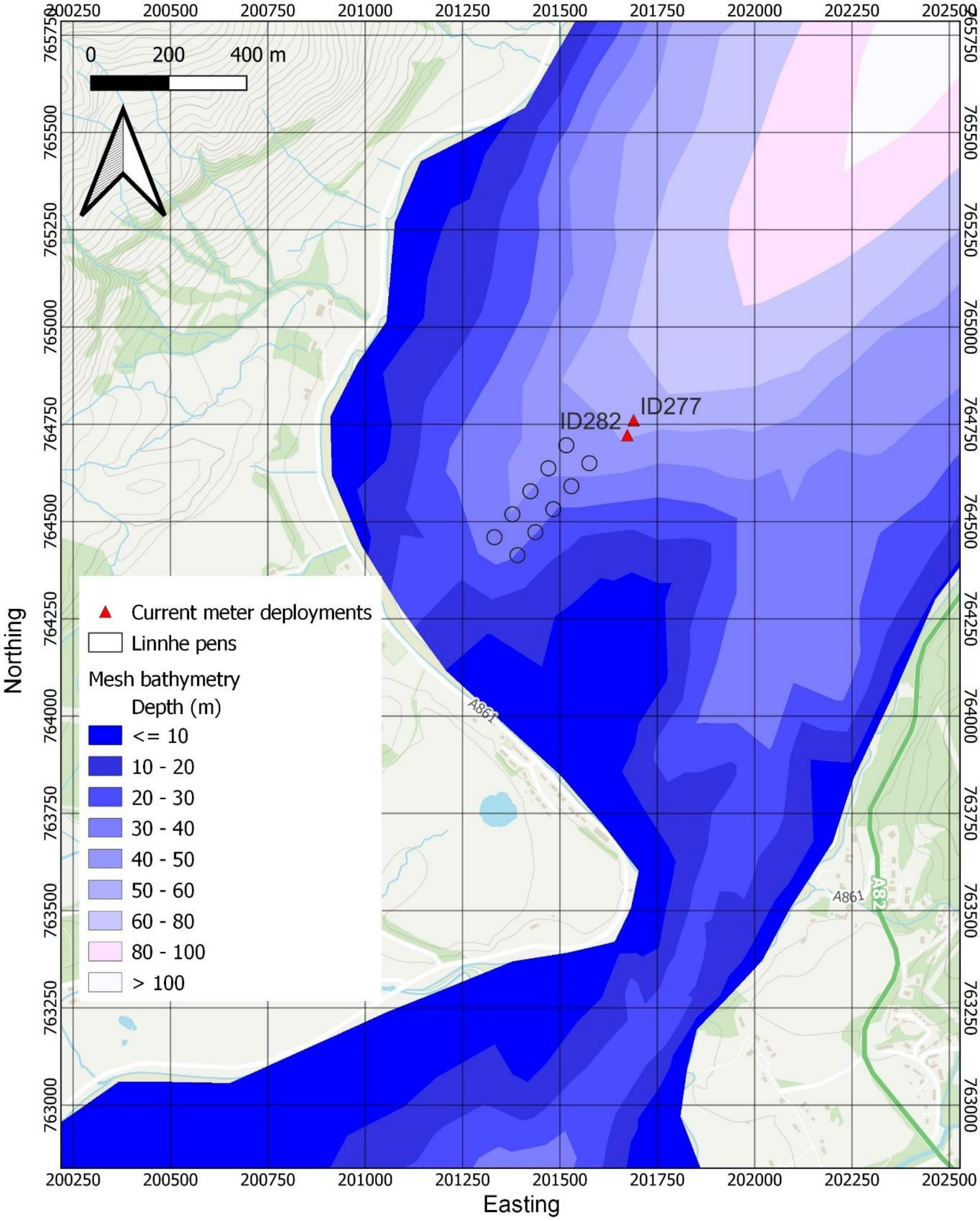


Figure 5. Model bathymetry depths (m) around Ardgour (Linnhe) in the area around the existing salmon farm. The existing pens at Ardgour (Linnhe) (○) and the ADCP deployment locations ID277 (▲) and ID282 (▲) are indicated.

4.2 Model Comparison

The hydrodynamic model will be calibrated against current data and seabed pressure data, measured in the Ardgour (Linnhe) area using Acoustic Doppler Current Profilers (ADCP, *Figure 5*). Data are available from:

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

In total, the data extend over 115 days.

5. DESCRIPTION OF THE PARTICLE TRACKING MODEL

Bath medicine dispersion modelling will be undertaken using a particle tracking model coupled with the hydrodynamic model flow fields described above to simulate the dispersion of bath medicine from the pens following treatment. The dispersion model has been developed from an earlier particle-tracking model code that has been used to simulate the transport and dispersal of pelagic organisms, including sea lice larvae (Gillibrand and Willis, 2007) and harmful algal blooms (Gillibrand et al., 2016a), and solute veterinary medicines (Willis et al., 2005) in Scottish coastal waters. The new model, UnPTRACK (Gillibrand, 2022), has been developed to use flow data from unstructured mesh hydrodynamic models. The model approach for a veterinary medicine is the same as for live organisms except that the medicine has no biological behaviour but instead undergoes chemical decay; the numerical particles in the model represent “droplets” of medicine of known mass, which reduces over time at a rate determined by a specified half-life. Particles are released at pen locations at specified times, according to a treatment schedule. The number of particles combined with their initial mass represents the mass of medicine required to treat a pen. The particles are then subject to advection, from the modelled flow fields, and horizontal and vertical diffusion. Particle locations are tracked throughout the simulation and output to file every hour, together with particle properties such as particle age and the mass of medicine represented (subject to decay). From the particle locations, concentrations of medicine are calculated and compliance with Environmental Quality Standards (EQS) assessed.

The particle-tracking model will use the same numerical grid as the hydrodynamic model, with the modelled velocity fields used to advect the numerical particles.

Within the particle tracking model, particles are advected by the velocity field and mixed by horizontal and vertical eddy diffusion, simulating the physical transport and dispersion of the cells. The mathematical framework of the model follows standard methodology for advection and diffusion of particles (e.g. Allen, 1982; Hunter et al., 1993; Ross and Sharples, 2004; Visser, 1997), whereby the location $X^{t+\Delta t}_P = X^{t+\Delta t}_P(x,y,z)$ of particle P at time t+Δt, can be expressed as:

$$X_P^{t+\Delta t} = X_P^t + \Delta t\left[\vec{U}_P + w_P\right] + \delta_H + \delta_Z \qquad (1)$$

where $\vec{U}_{\boldsymbol{P}}(x,y,z)$ is the 3D model velocity vector at the particle location, w_p is an additional vertical motion term due to, for example, particle settling or vertical migration and Δt is the model time step. Particle advection is treated using a fourth-order Runge-Kutta algorithm.

Horizontal and vertical eddy diffusion are represented in the model by the “random walk” displacements δ_H and δ_Z respectively, given by (Proctor et al., 1994):

$$\delta_H = R[6.K_H.\Delta t]^{1/2}$$
$$\delta_Z = R[6.K_Z.\Delta t]^{1/2} \quad (2)$$

where R is a real random number uniformly distributed over the range -1 ≤ R ≤ 1, and K_H and K_Z are the horizontal and vertical eddy diffusivities respectively. For the present simulations, we use a small constant eddy diffusivity of K_H = 0.1 m^2 s^{-1}.

A dye release study was conducted at Ardmucknish Bay using Rhodamine-WT dye in October 2019 on the East side of Loch Linnhe (Dale et al., 2020). The report from this study proposes that 0.1 m^2s^{-1} appears to be an appropriate conservative estimate for modelling the first 2-3 hours following a bath treatment

The choice of vertical diffusion coefficient is less certain but a value of K_V = 0.001 m^2s^{-1} is thought to be reasonably conservative for near-surface waters.

In Equation (1) for solute substances, w_p represents additional vertical motion of the particle due to, for example, buoyancy. For the present simulations, w_p = 0 since the bath treatments simulated here are administered in the cages with the medicine mixed into ambient seawater.
Chemical decay is simulated by varying the particle properties. At the time of release, each numerical particle represents a mass, M_0, of azamethiphos (active ingredient of Salmosan). The age since release, t_p, of every particle is stored, and the chemical mass, M_P, represented by each particle changes according to:

$$M_P = M_0 e^{\gamma t_p} \quad (3)$$

where γ = ln(0.5)/T_D and T_D is the half-life of the chemical decay. The mass M_P of every particle is stored in each output file.

For deposition modelling, UnPTRACK contains a bed model in which up to 10 sediment layers can be defined and which allow consolidation and erosion of deposited waste material.

The model has tested for accuracy in simulating advection, diffusion and chemical decay (Gillibrand, 2022). The random walk algorithm correctly simulated the increase in particle variance with specified horizonal dispersion coefficients of 0.1 m^2s^{-1} and 1.0 m^2s^{-1}. Chemical decay was similarly tested and the modelled concentration decayed with the specified half-life. These tests are not reported further here but are described by Gillibrand (2022).

6. BATH TREATMENT DISPERSION MODELLING

6.1 24-hour EQS

Modelling of bath treatments will be undertaken using a particle tracking model, UnPTRACK (Gillibrand, 2022), forced by the flow fields from the hydrodynamic model described above, to simulate the discharges and subsequent compliance with the EQS.

To simulate the worst-case scenario, the dispersion modelling will initially be conducted using flow fields over a period of 14 days centred on a small neap tidal range taken from the hydrodynamic model simulations. This is assumed to be the least dispersive set of ambient conditions, when medicine dispersion is least likely to meet the required EQS.

A treatment depth of 5m will be chosen initially as a realistic depth during application of the medicine for 120 m circumference pens. The initial mass released per pen is calculated from the reduced pen volume and a treatment concentration of 100 µg/L, with a total mass of 5.73 kg of azamethiphos released during treatment of the whole farm (10 pens). The number of cage treatments that can be performed in a single day will be determined by the modelling but is expected to be just one. Particles are released at random positions within a cage radius of the cage centre and within the 0 – 5 m depth range.

The length of the model simulations will depend on the treatment schedule, but will include the treatment period, a dispersion period to the EQS assessment at 72 hours after the final treatment, and an extra 24 hours to check for chance concentration peaks. Every hour of the simulation, particle locations and properties (including the decaying mass) will be stored and subsequently concentrations calculated. Concentrations will be calculated over the same depth range as the treatment is applied (i.e. 0 – 5 m).

From the calculated concentration fields, time series of two metrics will be constructed for the whole simulation:

(i) The maximum concentration (µg/L) anywhere in the model domain;
(ii) The area (km^2) where the EQS is exceeded.

These results will be used to assess whether the EQS or maximum allowable concentration (MAC) is likely to be breached after the allotted period (72 hours after the final treatment).

Sensitivity analyses will investigate the effects of:

(i) The decay rate (half-life) of azamethiphos;
(ii) The horizontal diffusion coefficient;
(iii) The vertical diffusion coefficient;
(iv) The tidal state at time of release. Simulations will be performed with the release times varied by ±2, ±4 and ±6 hours.

All simulations, aside from the time sensitivity analysis, will be repeated for a spring tide period and a second neap tide period.

6.2 3-hour EQS

The UnPTRACK model will also be used to assess the 3-hour EQS. The 3-hour mixing zone will be taken from the BathAuto excel spreadsheet using a mean surface speed of 11.1 cm s^1 from ID277, which is thought to be representative of the 0-5m surface layer at Ardgour (Linnhe). The model will output every 20 minutes (rather than hourly) and concentrations from these simulations will be calculated on a smaller (10m x 10m) grid to that used in the 72-hour model runs, this will be to more accurately calculate the smaller areas of medicine over the initial 3-hour period. Time series over spring and neap tides of the area where the 3-

hour EQS of 250 ng L^{-1} is exceeded and the peak concentration for each individual pen treatment will be shown.

7. DATA REQUIREMENTS FOR SIMULATIONS

7.1 Hydrographic Data

Current data collected at the farm site are used to characterise the local flow field. This information is essential for assessing the impact from fish farm discharges. All current meter deployments that will be used in the modelling for this site used a Teledyne RDI Sentinel V100 Acoustic Doppler Current Profiler, which Mowi Scotland now use as standard in all deployments. These instruments are deployed in mooring frames with 20^{o} free gimbal movement that automatically levels the instrument when deployed on the seabed.

Meters were set up to meet the requirements outlined in the SEPA guidance (SEPA, 2019) as far as possible whilst also ensuring that data quality was not compromised. Data will be processed in the usual fashion to the level of the SEPA HG-analysis spreadsheet. The individual HG-analysis files will be reported to SEPA with the CAR application.

8. MODEL OUTPUTS

8.1 Model Comparison

Model comparison will be carried out for the hydrodynamic model. Field current meter data will be compared to model values. A comparative performance of ≤ 10% variation for 90% of the combinations evaluated is desired but represents a high bar in these environments.

8.2 Model Results

Model results will be provided to SEPA in the form of selected (due to large file sizes) raw output files (comparison and bath medicine baseline runs only). Plots of results for all simulations will be provided and time series data files of key model results (e.g. predictions of bath medicine peak concentration and area exceeding the EQS) will be provided for all runs. The results from all model runs will be written up in the submitted application report.

8.3 Quality Assurance

The WeStCOMS model is in regular use in the academic modelling community, results from it are regularly published and cited in the peer-reviewed scientific literature. It was initially used for modelling harmful algal blooms (Aleynik et al. 2016). Recently, WeStCOMS flow fields have been used to simulate transport and beaching of litter (Allison et al. 2022), bivalve larvae dispersal (Corrochano-Fraile et al. 2022) and salmon farm connectivity (Aleynik et al. 2022).

Local model validation with dye has taken place in the context of the South of Loch Linnhe and WeStCOMS (Dale et al. 2020, Davidson et al. 2021). Validation has also taken place using CTD data from nearby Marine Protected Areas (Lavender et al. 2022) as well as historically with multiple drifter data sources.

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