Hydrodynamic and Bath Medicine Dispersion Modelling at Aird Point (Etive 4) and Sailean Ruadh (Etive 6) sites

METHOD STATEMENT

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1 INTRODUCTION

This method statement presents the specifications and rationale for use of a hydrodynamic (HD) model coupled with the particle-tracking model, UnPTRACK, to simulate the discharge, dispersion and fate of residues of bath medicines at two Mowi Scotland fish farm sites – **Aird Point (Etive 4)** and **Sailean Ruadh (Etive 6)** situated in **Loch Etive**. 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 both sites in order to apply for an increase to the current Azamethiphos limit that meets regulatory requirements, is in balance with the surrounding marine environment, and which is compliant with SEPA's EQS standards.

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

- Hydrodynamic modelling; choice of model; configuration; boundary conditions; calibration and validation;
- Bath modelling using a particle-tracking approach;
- Data collection, principally hydrographic data.

2 SITE PROPOSAL

The current Aird Point (Etive 4) and Sailean Ruadh (Etive 6) layouts consist of 6 x 120 m circumference pens (Figure 1). The Aird Point (Etive 4) site has a consented maximum allowable biomass of 1,545 T and Sailean Ruadh (Etive 6) has a consented maximum allowable biomass of 1,500 T. Mowi Scotland have upgraded the equipment at Aird Point (Etive 4) and Sailean Ruadh (Etive 6) to 6 x 120 m circumference pens and hence this application will seek to increase the consented Azamethiphos limit to a useable amount for the larger pens. The sites currently have a 24-hour Azamethiphos consent of 305.6 g (611.2 g of Salmosan) for Aird Point (Etive 4) and 238.7 g (477.4 g of Salmosan) for Sailean Ruadh (Etive 6). No increase in biomass will be applied for.

Table 1. Details of the proposed layout at Aird Point and Sailean Ruadh

SITE DETAILS		
Site Name:	**Sailean Ruadh**	**Aird Point**
Sites Location:	Loch Etive	Loch Etive
Proposed Treatment Use:	Azamethiphos	Azamethiphos
Peak Biomass (T):	1,500	1,545
Feed load (T/year):	3,833	3,947
Group Location:	198350, 734160	199160, 733980
Number of Pens:	6	6
Pen Circumference (m):	120	120
Grid Matrix (m):	75	75
Working Depth (m):	17	17
Pen Group Configuration:	2 x 3	2 x 3
Pen Group Distance to Shore (km):	121	111

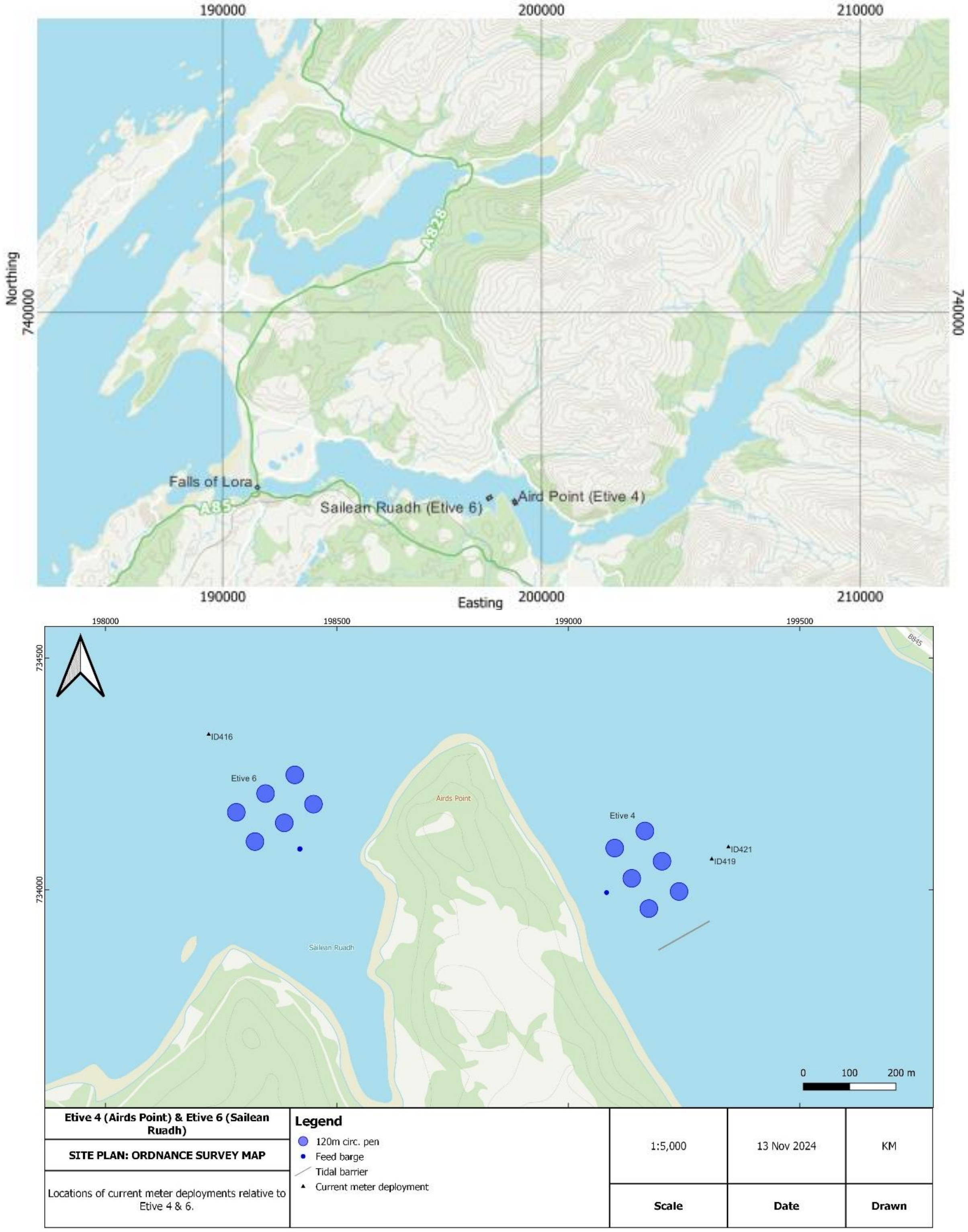

Figure 1. Locations of the two sites in Loch Etive (top). The current pen layouts at Aird Point (Etive 4) and Sailean Ruadh (Etive 6) with current meter positions shown by the black triangles (bottom).

3 HYDRODYNAMIC MODEL DESCRIPTION AND CONFIGURATION

Loch Etive is an extremely challenging environment for hydrodynamic models to simulate. The shallow entrance sill at the Falls of Lora, Connell (Figure 1), has a strong tidal choking (Stigebrandt, 1980) effect, leading to a 50% reduction in the tidal range within Loch Etive relative to the range in the adjacent coastal waters (Edwards and Edelsten, 1977). The very strong frictional forces at these locations tend to destabilise coastal hydrodynamic models, possibly because non-hydrostatic effects are so strong. As a result, the frictional effects must necessarily be diminished within the model and the simulated tidal choking not as strongly reproduced as in reality. For example, we need to impose a minimum water depth of 5 m within the model domain, which is deeper than the actual depths in the Falls of Lora, in order to keep the model stable. While this leads to relatively poor simulation of the sea surface height (SSH) within the loch, tidal choking effects on current speed and direction are very localized at the sill, and the hydrodynamic models are still able to simulate water velocity reasonably well within and outside the loch.

For example, the Wider Loch Linnhe System (WLLS) model does not fully reproduce the tidal choking effect on the SSH in Loch Etive, with the simulated tidal range noticeably greater than the observed range (Figure 2). However, some choking does occur, with the tidal amplitude in the loch reduced relative to that outside the loch. Importantly, the model still reproduces the magnitude of the current speed and direction within the loch reasonably well, although there is some offset due to an over-estimated density-driven circulation.

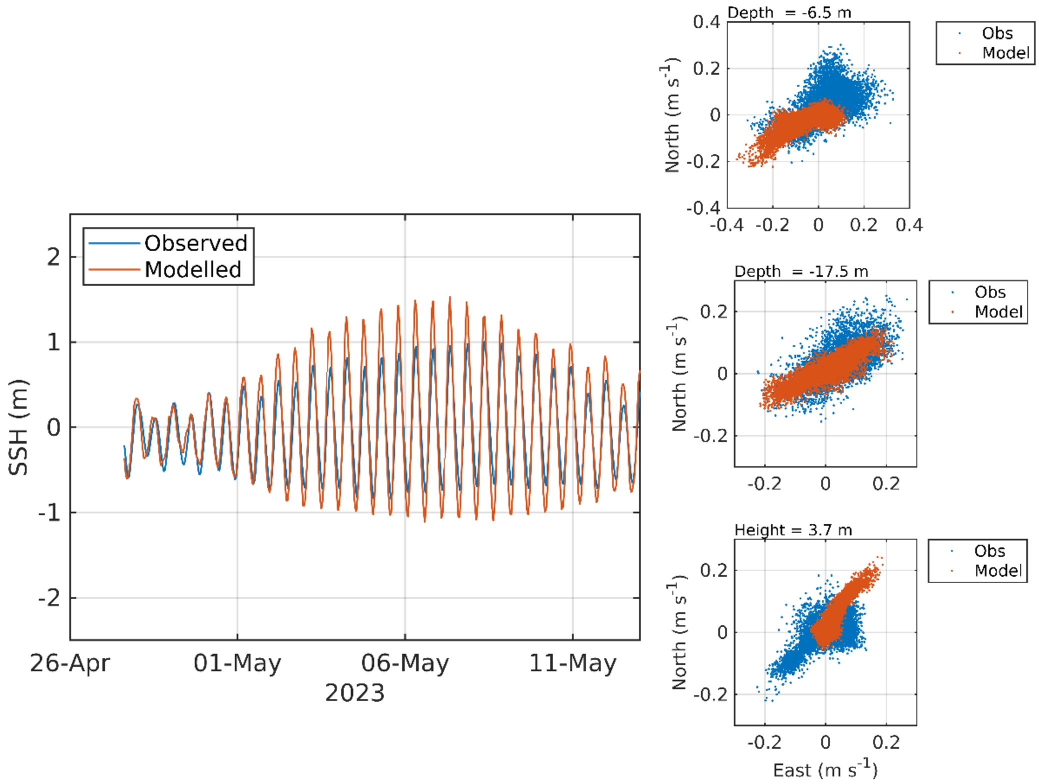

Figure 2. Comparison between modelled output from the WLLS model (red) line and observational data (blue) collected at Sailean Ruadh (Etive 6) from 27th April – 27th July 2023. Left: 15 days of sea surface height (SSH, m); Right: scatter plot of velocity data at 3 depths. The tides for the WLLS model have been adjusted from 1993 to 2023.

Medicine dispersion is predominantly driven by current speed and direction, and is relatively uninfluenced by sea surface height. Therefore, for the purposes of this study, we will focus the model calibration on velocity and not attempt to force the model to reproduce the full tidal choking effect on sea surface height.

We will explore two hydrodynamic models, RiCOM and FVCOM, to assess which is best able to most accurately reproduce the observations and will therefore be used in the bath modelling. In this Method Statement, we outline briefly the configuration of both models. The eventual configuration of the selected model will be fully described in the Hydrodynamic Model Description report.

1.1 The RiCOM Model

RiCOM (River and Coastal Ocean Model) is a general-purpose hydrodynamics and transport model, which solves the standard Reynolds-averaged Navier-Stokes equation (RANS) and the incompressibility condition, applying the hydrostatic and Boussinesq approximations. It has been tested on a variety of benchmarks against both analytical and experimental data sets (e.g. Walters & Casulli 1998; Walters 2005a, b). The model has been previously used to investigate the inundation risk from tsunamis and storm surge on the New Zealand coastline (Walters 2005a; Gillibrand et al. 2011; Lane et al. 2011), to study tidal currents in high energy tidal environments (Walters et al. 2010) and, more recently, to study tidal energy resource (Plew & Stevens 2013; Walters et al. 2013; Walters 2016) and the effects of energy extraction on the ambient environment (McIlvenny et al. 2016; Gillibrand et al. 2016a).

The equations are discretized on an unstructured grid of triangular elements which permits greater resolution of complex coastlines. The momentum and free surface equations are solved using semi-implicit techniques to optimize solution time and avoid the CFL stability constraint (Walters 2016). The material derivative in (2) is discretized using semi-Lagrangian methods to remove stability constraints on advection (Casulli, 1987; Walters et al. 2008). The Coriolis term is solved using a 3rd order Adams-Bashforth method (Walters et al. 2009). Full details of the model discretization and solution methods can be found in Walters et al. (2013) and Walters (2016). The solution methods provide a fast, accurate and robust code that runs efficiently on multi-core desktop workstations with shared memory using OpenMP.

1.2 The FVCOM Model

FVCOM (Finite Volume Community Ocean Model) 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 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. Horizontal viscosity and diffusivity is parameterised using a Smagorinsky scheme, with a coefficient c_s. 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 finitedifference 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 make 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.

1.3 Model Configuration

The unstructured mesh used in the modelling (Figure 3) was adapted from a custom Loch Linnhe mesh subdomain of the Wider Loch Linnhe System (WLLS), with open water boundaries in the Firth of Lorn and the Sound of Mull. The model resolution was enhanced in the Loch Etive region, particularly around the Mowi sites, Aird Point (Etive 4) and Sailean Ruadh (Etive 6) (Figure 4). The spatial resolution of the model varied from 29 m in some inshore waters and round the farm pens to 180 m along the open boundary. The model consisted of 33,393 nodes and 59,893 triangular elements. The model will be run in either 2D mode in RiCOM or 3D mode in FVCOM, depending on the goodness-of-fit to the data. Model bathymetry (Figure 5) was also taken from the WLLS model with the addition of bathymetry data collected from a multibeam depth survey available through the Admiralty Seabed Mapping Service (Seabed Mapping Service, 2024).

The model is forced at the outer boundaries by 8 tidal constituents (M_2, S_2, N_2, K_2, O_1, K_1, P_1, Q_1) which were derived from tidal analysis (Pawlowicz et al., 2002) of the sea surface elevations at the closest nodes from the Wider Loch Linnhe System climatology (Marine Scotland, 2016). Spatially- and temporally-varying wind speed and direction data are taken from the Scottish Coastal Ocean and Atmospheric Modelling Service (WeStCOMS-WRF, 2024) for the required simulation periods.

The 3D FVCOM implementation will include freshwater flows into the sea, and will be generated either from gauged river flow data or from the climatology used in the Marine Directorate WLLS model.

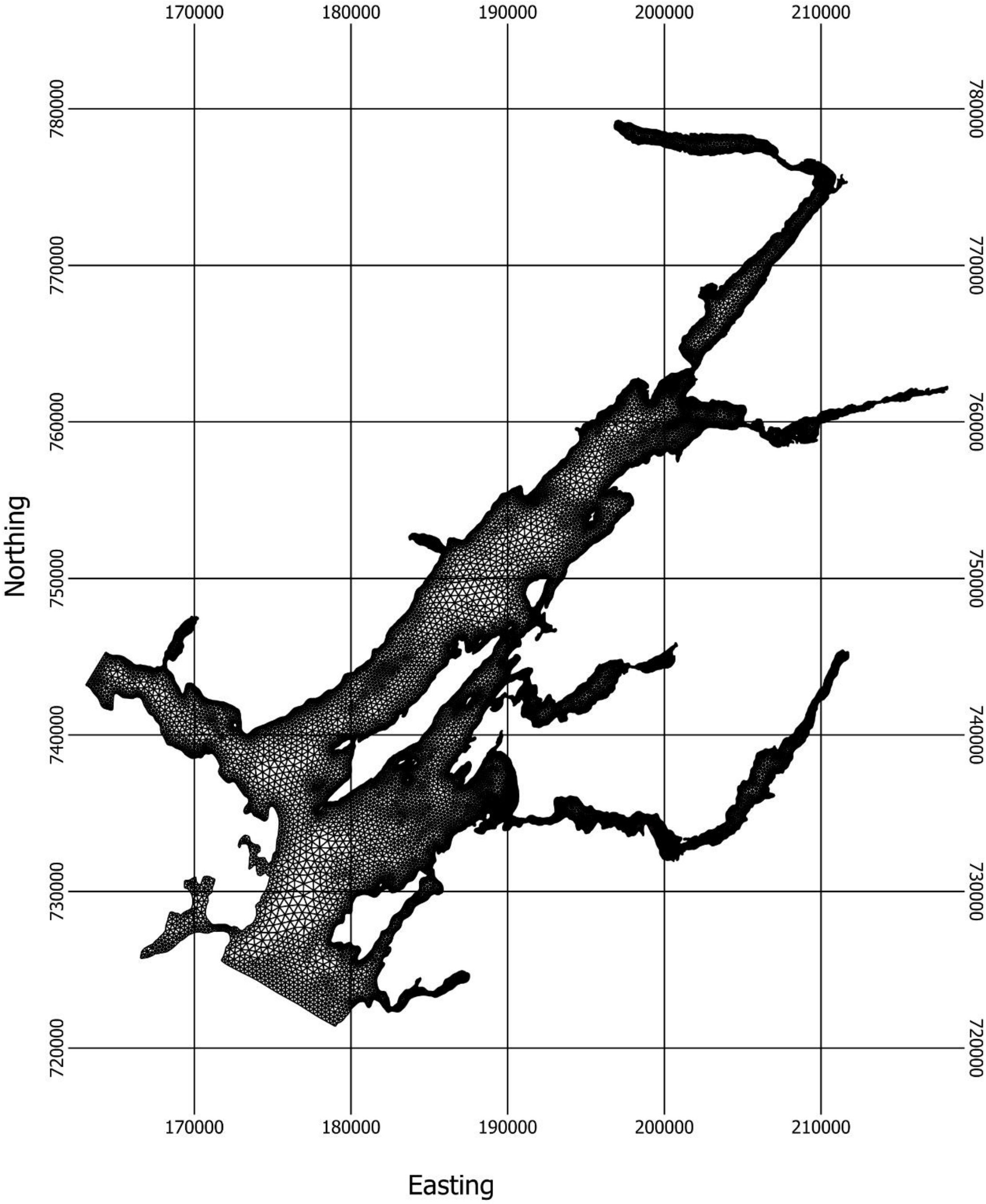

Figure 3. The Loch Etive mesh and domain of the modelling study.

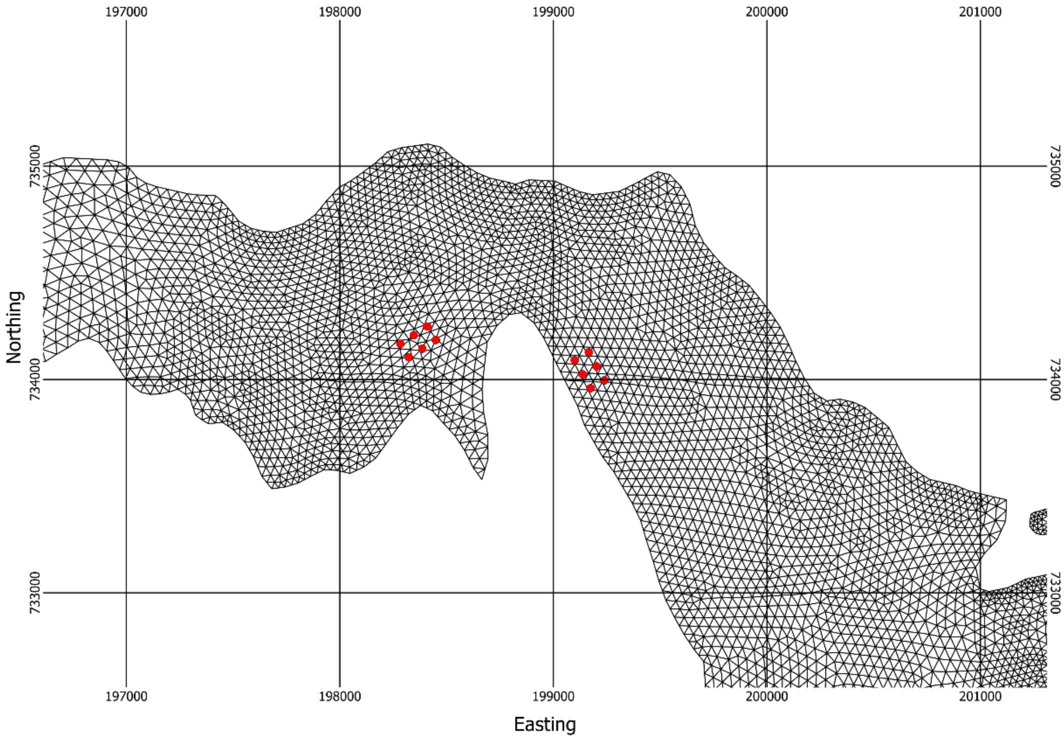

Figure 4. The unstructured mesh around the Aird Point (Etive 4) and Sailean Ruadh (Etive 6) sites in the modified model grid, with the pen locations indicated (●).

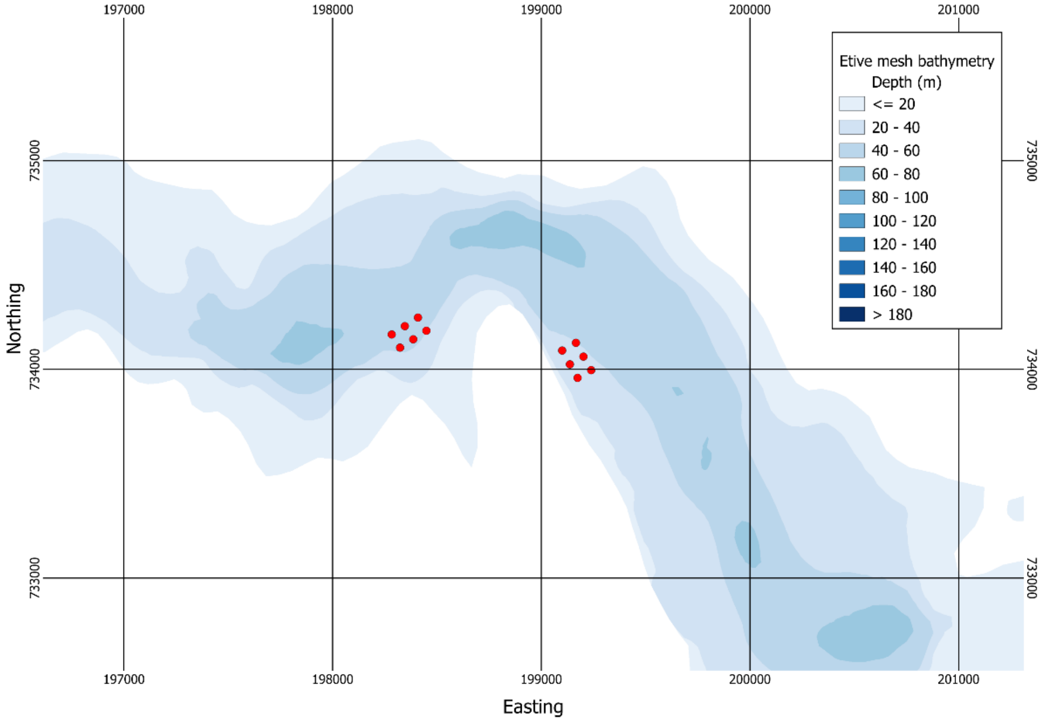

Figure 5. Model water depths (m) in the area around the Aird Point (Etive 4) and Sailean Ruadh (Etive 6) salmon farm sites. The pen locations are indicated (●).

1.4 Model Calibration

The local area model will be calibrated against current data and seabed pressure data, measured near the two sites using Acoustic Doppler Current Profilers (ADCP), see Figure 1 for ADCP locations. Data are available from:

(i) Calibration: April 2023 – July 2023 (ID416)
(ii) Validation: August 2023 – October 2023 (ID421)

In total, the data extend over 156 days. Calibration will be performed in a standard fashion, with bed friction being adjusted using the drag coefficient, C_D, to obtain the best fit against the sea surface height and current data. Once the best comparison with the calibration data has been achieved, the parameter set will be tested without further adjustment against the validation dataset.

2. 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., 2016b), 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.

Velocity data to drive the model can be obtained from current meter (ADCP) observations or from hydrodynamic model simulations. In the case of the latter, 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. In the case of the former, a numerical grid is constructed to cover the area of the simulated dispersion, and the observed current data applied at each of the grid nodes; in this case, the velocity field experienced by the numerical particles is spatially non-varying in the horizontal, although vertical shear can be present if multiple current meters, or multiple bins from an ADCP deployment, are used. In both cases, realistic bathymetry can be used, although this is not expected to be a critical factor in the dispersion of bath treatments.

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:

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

where $\vec{U}_P$(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 $-1 \leq R \leq 1$, 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}.

The choice of vertical diffusion coefficient is less certain but a value of $K_V = 0.001$ m^2 s^{-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 $\gamma = \ln(0.5)/T_D$ and T_D is the half-life of the chemical decay. The mass M_P of every particle is stored in each output file.

The model has tested for accuracy in simulating advection, diffusion and chemical decay (Gillibrand, 2021). The random walk algorithm correctly simulated the increase in particle variance with specified horizonal dispersion coefficients of 0.1 m^2 s^{-1} and 1.0 m^2 s^{-1}. Chemical decay was similarly tested and the modelled concentration decayed with the specified half-life. A dye study was performed at the nearby North Shore East site between 21st and 24th July 2020, this gave a mean horizontal diffusion coefficient of 0.060 m^2 s^{-1} (AMSL, 2020) and this will be used as part of the sensitivity runs in the bath modelling. These tests are not reported further here but are described by Gillibrand (2021).

3. BATH TREATMENT DISPERSION MODELLING

3.1 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 10 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 5 m will be chosen 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^{-1}, with a total mass of 3.44 kg of azamethiphos released during treatment of all 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 1 or 2 at a minimum of 3-hour intervals. 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 25 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 surface 5 m water column (i.e. depths 0 – 5 m).

From the calculated concentration fields, time series of two metric 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 horizontal diffusion coefficient;
(ii) The vertical diffusion coefficient;
(iii) The tidal state at time of release. Simulations will be performed with the release times varied by ±2, ±4 and ±6 hours.

All simulations, including the sensitivity analysis, will be repeated for a spring 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 17.3 cm s^{-1} from ID421 and 10.9 cm s^{-1} from ID416, which is thought to be a conservative representation of the 0 - 5 m surface layer at Aird Point (Etive 4) and Sailean Ruadh (Etive 6) respectively.

The model will output every 20 minutes (rather than hourly) and concentrations from these simulations will be calculated on a finer (10m x 10m) grid than 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.

4. DATA REQUIREMENTS FOR SIMULATIONS

4.1 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. In particular, current data are used in the modelling of dispersion of dissolved and solid substances. 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° 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, 2022) as far as possible whilst also ensuring that data quality was not compromised. ID416 and ID421 will be used together in the bath modelling. 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.

5. MODEL OUTPUTS

5.1 Model Calibration and Validation

Model calibration will be carried out for the hydrodynamic model. Field current meter data will be compared to model values. The model will be run in a hindcasting mode, over the same time period as the meter data was collected. Once a parameter set is selected via the calibration process, independent validation simulations, using exactly the same parameter set, will be performed against a separate current meter dataset and quantitative assessment of model performance undertaken. The calibration and validation procedure, and performance of the model, will be submitted to SEPA in a report with the application.

5.2 Quality Assurance

Quality assurance information is not available for the hydrodynamic modelling package; however, the model is in regular use in the academic modelling community, is regularly published and cited in the peer-reviewed scientific literature, and is being actively used and developed.

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