Medicine Dispersion Modelling
Tabhaigh, Loch Erisort
CAR/L/1129793

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Tabhaigh salmon farm will comply with pertinent Environmental Quality Standards (EQS). A realistic treatment regime, with 1 pen treatment per day was simulated. Each pen required 1021 g of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) or 20.4 g of deltamethrin for treatment, resulting in a daily release of 1021 g and a total discharge over 7 days of 8.17 kg for azamethiphos and separately 0.204 kg of deltamethrin over 7 days. Simulations were performed separately for modelled neap and spring tides, and the sensitivity of the results to key model parameters was tested.

The model results (Table 1) confirmed that the treatment scenario proposed, with a daily release of no more than 1021 g of azamethiphos should comfortably comply with the EQS. The peak concentration during the baseline simulation 72 hours after the final treatment was less than 0.1 µg L^{-1}, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg L^{-1} was substantially less than the allowable 0.5 km^2 for both sites. The baseline simulation presented here was designed to be relatively conservative.

The 24-hour mass is substantially larger than the amount predicted by the standard bath model, but the latter is known to be highly conservative, because it does not account for horizontal shearing and dispersion of medicine patches due to spatially-varying current fields, processes which are known to significantly influence dispersion over time scales greater than a few hours.

Table 1. Summary of Results

Site Details	
Site Name:	Tabhaigh
Site Location:	Loch Erisort
Peak Biomass (T):	2,500
Pen Details	
Number of Pens:	8
Pen Circumference (m):	160
Working Depth (m):	20 and 15
Pen Group Configuration:	2 x 4
Azamethiphos Consent	
Recommended 3-hour (g):	1021
Recommended 24-hour (g):	1021
Deltamethrin Consent	
Recommended 3-hour (g)	20.4

1 INTRODUCTION

This report has been prepared by Mowi Scotland Ltd. to meet the requirements of the Scottish Environment Protection Agency (SEPA) for an application to increase the current consent of topical sea lice veterinary medicines at the marine salmon farm Tabhaigh, Loch Erisort (Figure 1). The report presents results from coupled hydrodynamic and particle tracking modelling to describe the dispersion of bath treatments to determine EQS-compliant quantities for the current site biomass and equipment. The modelling procedure follows, as far as possible, guidance presented by SEPA in December 2023 (SEPA, 2023b).

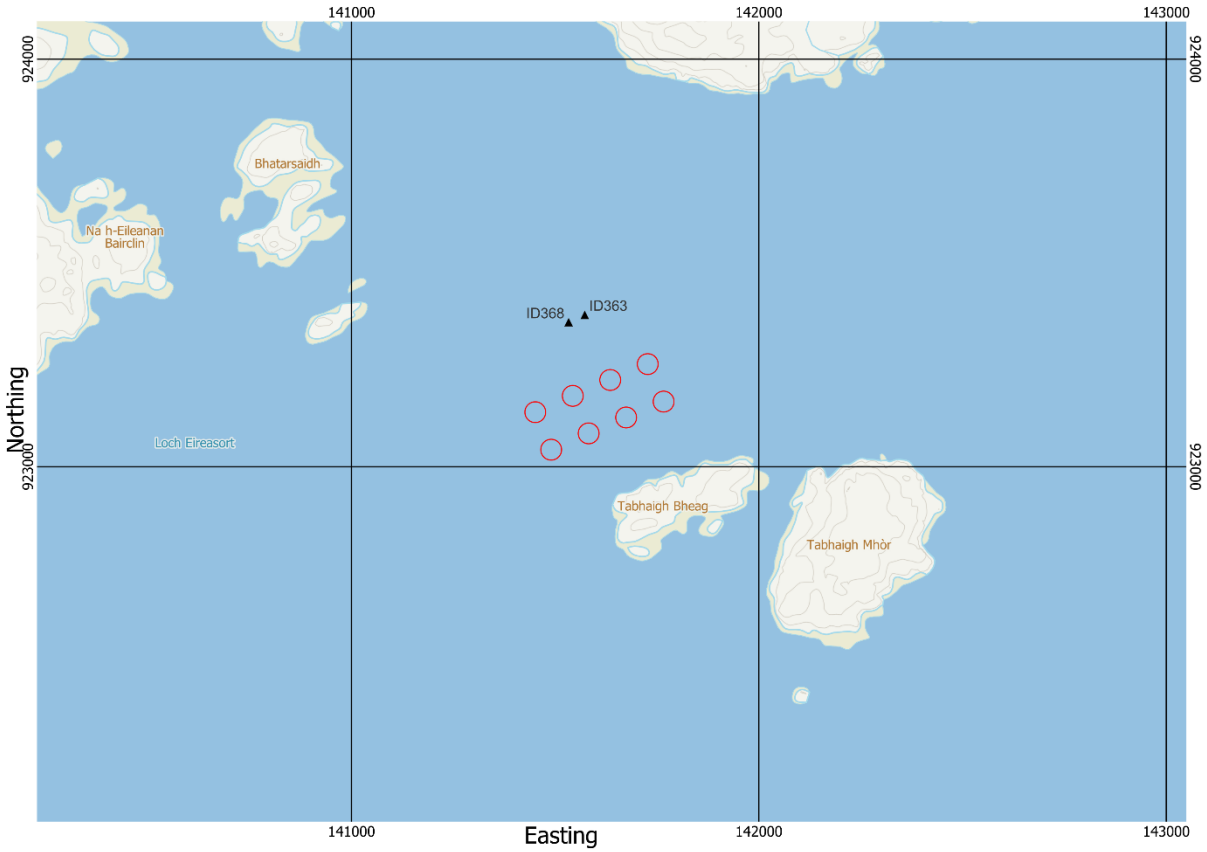

Figure 1. Location of Tabhaigh salmon farm and the location of the ADCP deployments (▲) relative to the proposed pen positions (o).

1.1 Site Details

The site is situated toward the mouth of Loch Erisort, immediately north of the island Tabhaigh Bheag (Figure 1). Details of the hydrographic data are provided in Table 2. The receiving water is defined as Loch Erisort.

Table 2. Hydrographic Information

Hydrographic Data		
	ID363	**ID368**
Site:	Tabhaigh	Tabhaigh
Current Meter Position:	141572E 923373N	141533E 923355N
Depth of Deployment Position (m):	37.38	40.66
Surface Bin Centre Height Above Bed (m):	28.72	30.72
Middle Bin Centre Height Above Bed (m):	16.72	19.72
Bottom Bin Centre Height Above Bed (m):	3.72	3.72
Duration of Record (days):	85.5	85.67
Start of Record:	09/11/2020 14:00	10/02/2021 13:00
End of Record:	03/02/2021 02:00	07/05/2021 05:00
Current Meter Averaging Interval (min):	20	20
Magnetic Correction to Grid North:	-3.5	-3.45

2. MODEL DETAILS

2.1 Model Selection

The modelling approach adopted a coupled hydrodynamic and particle tracking method, whereby water currents in the region, modelled using a calibrated hydrodynamic model, advected particles representing the topical medicine around the model domain. Turbulent eddy diffusion was modelled using a random walk method. Outputs from the modelling were derived to assess the dispersion of the medicine following treatments against statutory EQS. The modelling approach is described in full in the Hydrodynamic Model Description report (Mowi, 2024), and is only summarised here.

For the hydrodynamics, the RiCOM model was used. 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 (Walters and Casulli, 1998). It has been tested on a variety of benchmarks against both analytical and experimental data sets. The model has been previously used to investigate the inundation risk from tsunamis and storm surge on the New Zealand coastline, the effects of mussel farms on current flows, and, more recently in Scotland to study tidal energy resource and the effects of energy extraction on the ambient environment (McIlvenny et al., 2016; Gillibrand et al., 2016b).

The mathematical equations are discretized on an unstructured grid of triangular elements which permits greater resolution of complex coastlines, such as typically found in Scotland. Therefore greater spatial resolution in near-shore areas can be achieved without excessive computational demand.

For the particle tracking component, Mowi's in-house model UnPTRACK (Gillibrand, 2022) was used. The model used the hydrodynamic flow fields from the RiCOM model simulations. This model has been used previously to simulate sea lice dispersal (Gillibrand & Willis, 2007), the development of a harmful algal bloom (Gillibrand et al., 2016a) and the dispersion of cypermethrin from a fish farm (Willis et al., 2005). The approach for veterinary medicines is the

same as for living organisms, except that 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, horizontal and vertical diffusion, and chemical decay. Concentrations of medicine can be calculated throughout the simulation and compared with relevant EQS e.g. 72 hours after the final treatment. Here, the dispersion of azamethiphos following treatment scenarios at Tabhaigh has been modelled to illustrate the quantities of medicine that disperse safely in the environment.

2.1.1 Model Domain and Boundary Conditions

The unstructured mesh used in the model was adapted from the East Coast of Lewis and Harris (ECLH) sub-model mesh of the Scottish Shelf Model (SSM; Marine Scotland, 2016) (Figure 2). Model resolution was enhanced in the Loch Erisort region particularly around the Mowi site at Tabhaigh (Figure 3). The spatial resolution of the model varied from 21 m in some inshore waters to 3 km along the open boundary. The model consisted of 74,588 nodes and 141,229 triangular elements. Bathymetry was taken from The East Coast of Lewis and Harris model and local multibeam surveys (Figure 3). Given that topical medicine dispersion occurs in the upper water column, it was not deemed necessary to use highly detailed bathymetry data in the immediate vicinity to the pens.

Figure 2. The mesh and domain of the modelling study, adapted from The East Coast of Lewis and Harris model.

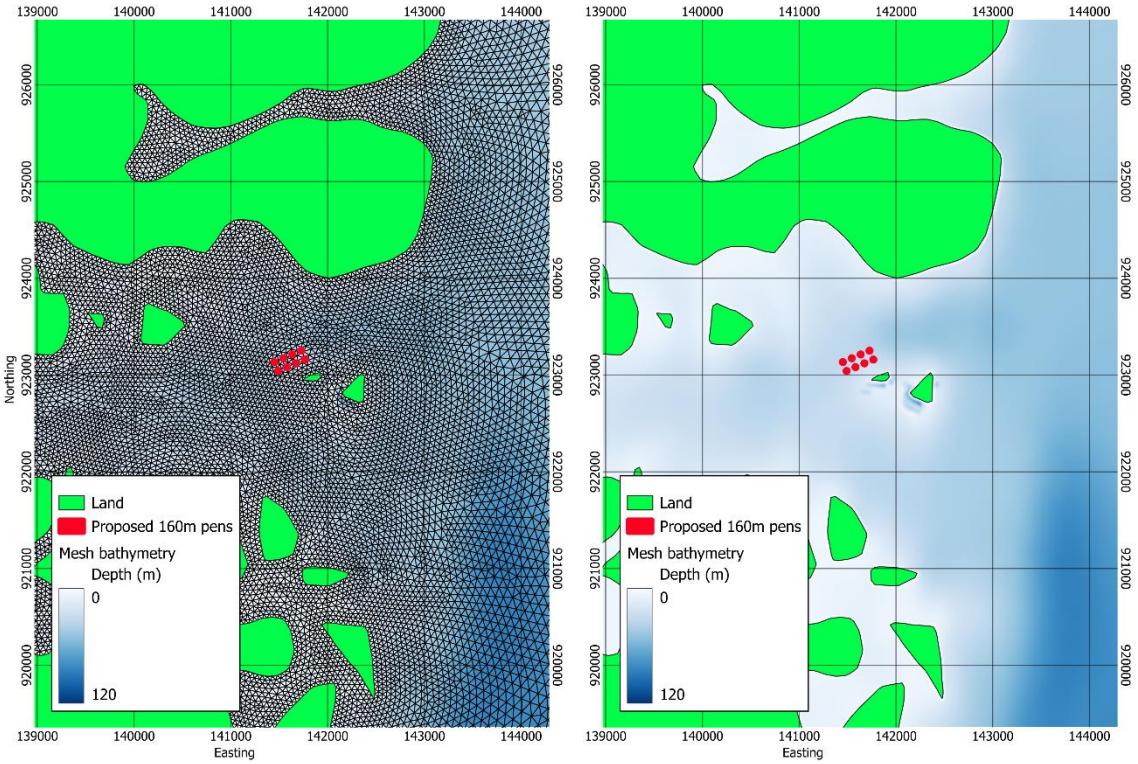

Figure 3. Model mesh (left) and water depths (m, right) in the area around the Tabhaigh site. The proposed pen locations are indicated (○).

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 Scottish Shelf Model climatology (Marine Scotland, 2016). Spatially- and temporally-varying wind speed and direction data are taken from the ERA5 global reanalysis dataset (ECMWF, 2021) for the required simulation periods.

Full details of the calibration and validation of the hydrodynamic model are given in the Tabhaigh Hydrodynamic Model Description (Mowi, 2024).

2.2 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the UnPTRACK model (Gillibrand, 2022), simulates the dispersion of patches of medicine discharged from pens following treatment using tarpaulins. The UnPTRACK model uses the same unstructured mesh as the hydrodynamic model, and reads the flow fields directly from the hydrodynamic model output files. Therefore, no spatial or temporal interpolation of the current fields is required, although current velocities are interpolated to particle locations within UnPTRACK. The treatment scenario assumed 1 pen can be treated per day.

To simulate the worst-case scenario, the dispersion modelling was initially conducted using flow fields over a period of 11 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. Later simulations tested dispersion during spring tides.

A treatment depth of 5 m was chosen as a realistic net depth during application of the medicine for the 160m pens. The initial mass released per pen was calculated from the reduced pen volume and a treatment concentration of 100 µg L^{-1}, with a total mass of 8.17 kg of azamethiphos released during treatment (8 pens). Particles were released from random positions within a pen radius of the centre and within the 0 – 5 m depth range. The simulations used *ca. 817,128* numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation ran for a total of 264 hours (11 days). This covered the treatment period (168 hours), a dispersion period to the EQS assessment after 72 hours after the final treatment, and an extra 24 hours to check for chance concentration peaks. At every hour of the simulation, particle locations and properties (including the decaying mass) were stored and subsequently concentrations calculated. Concentrations were calculated on a grid of 25 m x 25 m squares using a depth range of 5 m. Using a regular grid for counting makes calculating particle concentrations and presenting the results easier, and also provides consistent accuracy and precision in the calculated concentrations across the grid.

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

(i) The maximum concentration (µg L^{-1}) anywhere on the regular grid; and
(ii) The area (km^2) where the EQS was exceeded.

These results were used to assess whether the EQS or MAC was breached after the allotted period (72 hours after the final treatment).

Sensitivity analyses were conducted to assess the effects of:

(i) Medicine half-life
(ii) Horizontal diffusion coefficient, K_H
(iii) Vertical diffusion coefficient, K_V
(iv) Time of release

The dispersion simulations were performed separately over neap and spring tides during 2021 (ID368) (Figure 4). A further set of simulations were performed over neap tides in January 2021 (ID363) to confirm the adequacy of dispersion during the weakest tides (Figure 5).

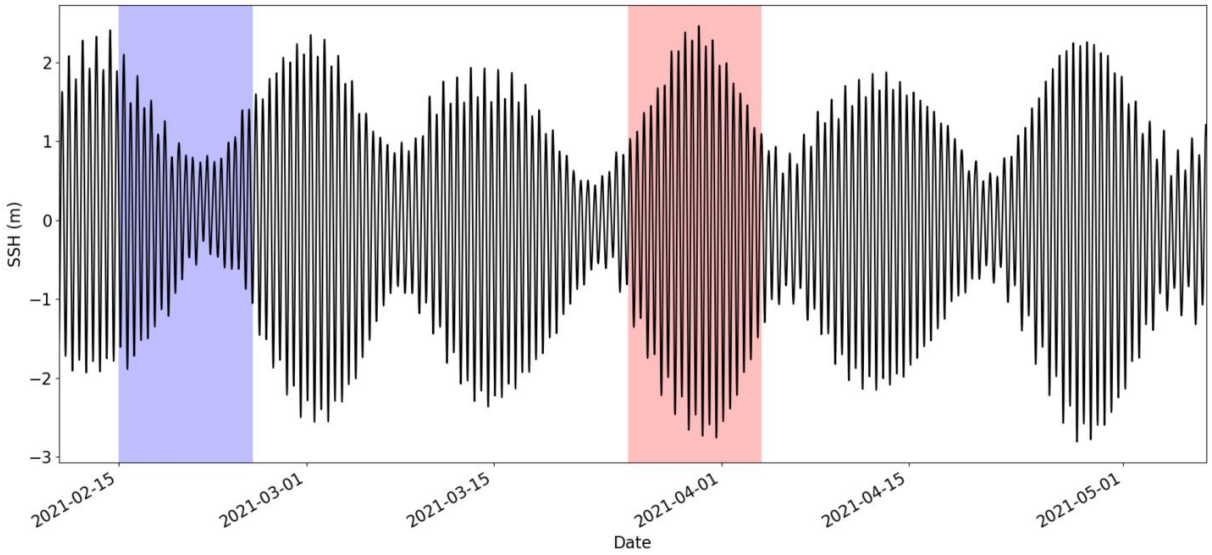

Figure 4. Sea surface height (SSH) at Tabhaigh from 10th February 2021 – 7th May 2021 (ID368). Dispersion simulations were performed over periods of neap tides (blue, start day 15th February 2021) and spring tides (red, start day 15th March 2021).

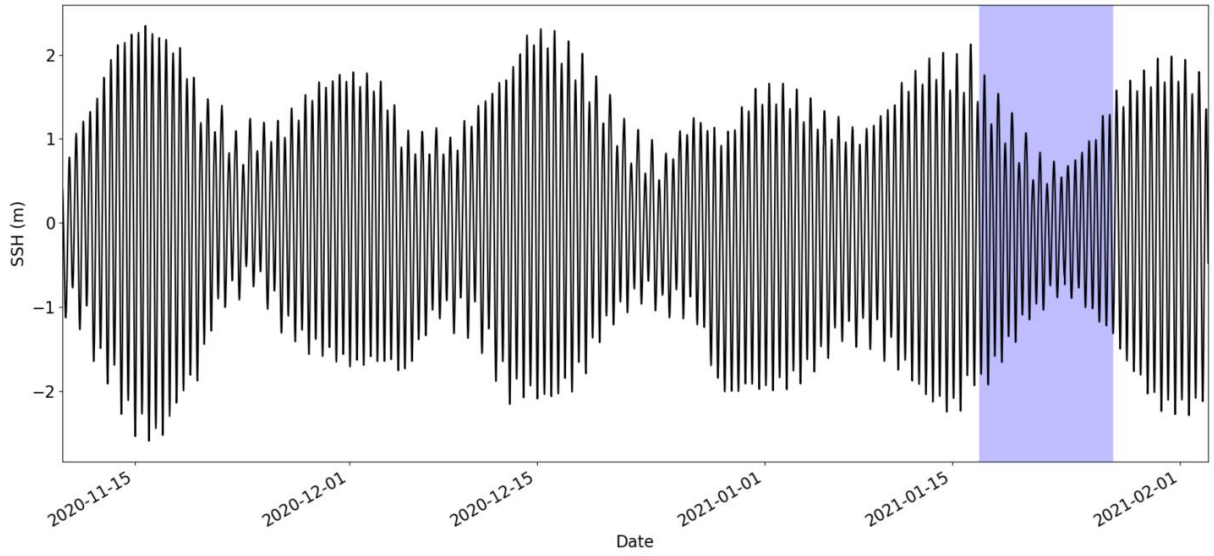

Figure 5. Sea surface height (SSH) at Tabhaigh from 9th November 2020 – 3rd February 2021 (ID363). Dispersion simulations were performed over periods of neap tides (blue, start day 16th January 2021).

2.3 Medicine Dispersion Simulations

The pen locations and details of the medicine source are listed in Table 3. The time of release is relative to the start of the neap or spring period highlighted in Figure 4 and Figure 5.

All simulations used the release schedule and quantities outlined in Table 3. In Runs 2 – 7 (Table 4), the release schedule was set back or forward by a number of hours to investigate the effect of tidal state at the time of release on the results. Results for these simulations are still presented in terms of time relative to the first release.

Table 3. Details of the treatment simulated by the dispersion model. The release time is relative to the start of the neap or spring period highlighted in Figure 4 and Figure 6.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (g)	Release Time (hr)
1	141451	923134	5	1021	0
2	141490	923042	5	1021	24
3	141543	923174	5	1021	48
4	141582	923082	5	1021	72
5	141635	923213	5	1021	96
6	141674	923121	5	1021	120
7	141727	923252	5	1021	144
8	141766	923160	5	1021	168

Table 4. Dispersion model simulation details for the treatment simulations of 8 pens at Tabhaigh.

Set	Run No.	$T_{1/2}$ (h)	K_H	K_V	Start Time
Neap Tides, Start day = 6 (15th February 2021, ID368)					
Baseline	1	134.4	0.1	0.001	00:00
1	2	134.4	0.1	0.001	00:00 -6h
	3	134.4	0.1	0.001	00:00 -4h
	4	134.4	0.1	0.001	00:00 -2h
	5	134.4	0.1	0.001	00:00 +2h
	6	134.4	0.1	0.001	00:00 +4h
	7	134.4	0.1	0.001	00:00 +6h
2	8	134.4	0.2	0.001	00:00
	9	134.4	0.05	0.001	00:00
3	10	134.4	0.1	0.0025	00:00
	11	134.4	0.1	0.005	00:00
Spring Tides, Start day = 44 (10th March 2021, ID368)					
5	12	134.4	0.1	0.001	00:00
6	13	134.4	0.2	0.001	00:00
	14	134.4	0.05	0.001	00:00
7	15	134.4	0.1	0.0025	00:00
	16	134.4	0.1	0.005	00:00
Neap Tides, Start day = 70 (16th January 2021, ID363)					
8	17	134.4	0.1	0.001	00:00
9	18	134.4	0.2	0.001	00:00
	19	134.4	0.05	0.001	00:00
10	20	134.4	0.1	0.0025	00:00
	21	134.4	0.1	0.005	00:00

2.4 Azamethiphos 3-hour EQS

In addition to the main simulations described above to assess compliance with the 72-hour EQS, simulations were also performed to assess compliance with the 3-hour EQS (SEPA, 2023b). The 3-hour EQS is applied as a mixing zone EQS, whereby the area where concentrations exceed the EQS of 250 ng L^{-1} after 3 hours must be less than the 3-hour mixing zone. The 3-hour mixing zone is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 6.67 cm s^{-1} was used from ID368 (Table 5).

Table 5. Parameter values used in the calculation of the 3-hour mixing zone ellipse area and the resulting area

Parameter	Value
Mean current speed (ms^{-1})	0.067
Area of 160m pen (km^2)	0.001446
Distance from shore (km)	0.145
Mean water depth (m)	33.5
Treatment Depth (m)	5
Mixing zone ellipse area (km^2)	**0.105631**

For the 3-hour EQS assessment, the baseline runs for neap and spring tides (Runs 1 and 12 in Table 4) were repeated, but with results output every 20 minutes and the runs were truncated, lasting only until 3 hours after the final treatment. The area of the medicine patch for each individual treatment was then calculated over the 3-hour period following its release, and the area exceeding 250 ng L^{-1} determined. Concentrations from these simulations were calculated on a 10 m x 10 m grid (rather than a 25 m x 25 m grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

2.5 Deltamethrin 6-Hour EQS

Simulations were also performed to assess compliance of deltamethrin treatments with the 6-hour EQS (SEPA, 2023b). The 6-hour EQS is applied as a mixing zone EQS, whereby the area where concentrations exceed the EQS of 6 ng L^{-1} after 6 hours must be less than the 6-hour mixing zone. The 6-hour mixing zone is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 6.67 cm s^{-1} was used from ID368 (Table 6).

Table 6. Parameter values used in the calculation of the deltamethrin 6-hour mixing zone ellipse area and the resulting area

Parameter	Value
Mean current speed (ms^{-1})	0.067
Area of 160m pen (km^2)	0.001446
Distance from shore (km)	0.145
Mean water depth (m)	33.5
Treatment Depth (m)	5
Mixing zone ellipse area (km^2)	**0.279202**

For the 6-hour EQS assessment, the baseline runs for neap and spring tides (Runs 1 and 12 in Table 4) were repeated, but with a treatment mass of 0.020 kg of deltamethrin. The medicine half-life was set to zero. Results were output every 20 minutes and the runs were truncated, lasting only until 6 hours after the final treatment. The area of the medicine patch for each individual treatment was then calculated over the 6-hour period following its release, and the

area exceeding 6 ng L^{-1} determined. Concentrations from these simulations were calculated on a 10 m x 10 m grid (rather than a 25 m x 25 m grid) in order to more accurately calculate the smaller areas of medicine over the initial 6-hour period.

2.6 Interactions with Identified Features

Two identified features (European Spiney Lobster and Kelp bed) at the same location have been identified (SEPA, 2023a) (Figure 6) which are thought to be at potential risk from medicine influence and hence must be considered when modelling the treatment releases from Tabhaigh.

Predicted concentrations of azamethiphos at the identified features during the simulation periods will be extracted, and the mean and maximum concentrations derived. The proportion of the PMF where the 3-hour (0.25 µg L^{-1}) and the 72-hour (0.10 µg L^{-1}) EQS are exceeded will be calculated. These calculations will be undertaken for a 5 m thick layer immediately above the seabed, since these special features are predominantly benthic habitats.

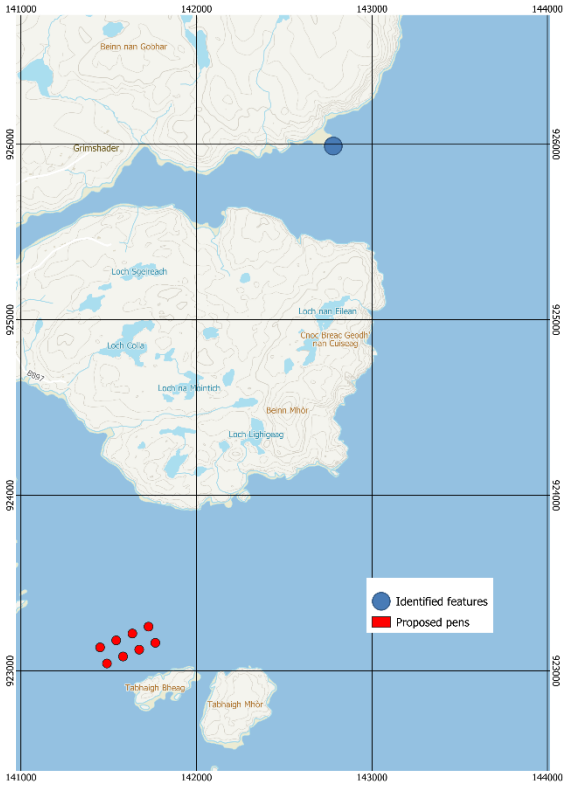

Figure 6. Identified features and Tabhaigh proposed pens

2.7 Diffusion Coefficients

Selection of the horizontal diffusion parameter, K_H, was guided by dye releases conducted at Tabhaigh by Anderson Marine Surveys Ltd. between 22nd and 24th July 2020, along with several other dye release studies undertaken at other salmon farm locations. Dye tracking studies proceed by releasing a known quantity of dye into the sea, and then attempting to map the resulting dye patch as it disperses over time by deploying a submersible fluorometer from a boat. Each survey of the patch takes a finite amount of time (typically less than 30 minutes) and is usually made up of several transects which attempt to criss-cross the patch. An estimate of horizontal diffusivity can be made from each transect, but the location of the transect relative to the centre of the patch (and the highest concentrations) is often uncertain. The estimates of horizontal diffusivity shown in Figure 7 come from these individual transects.

The analysis method is based on estimating the diffusion from individual transects through the dye patch from the variance in the dye concentrations along the transect. The dye survey at the Tabhaigh sites gave a mean horizontal diffusivity of **0.06 m^2 s^{-1}**. There is considerable scatter in the data (Figure 7), arising from the difficulty of tracking dye in the marine environment which renders individual values highly uncertain; this difficulty is exacerbated in Scotland due to the limited quantities of dye that are permitted to be released, making it difficult to visually track the dye and take measurements that encompass the patch.

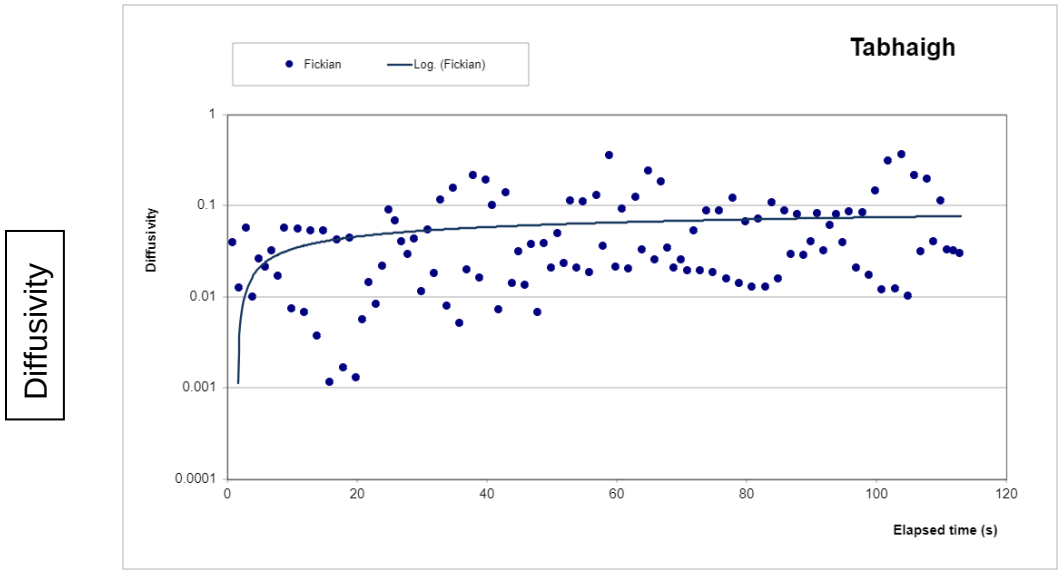

Figure 7. Estimated horizontal diffusivity (m^2 s^{-1}) from dye release experiments at the Tabhaigh site. The mean diffusivity was 0.06 m^2 s^{-1}.

A second method of analysis is also presented here. According to Fickian diffusion theory (Lewis, 1997), the maximum concentration, C_{max} in a patch of dye decreases with time according to:

$$C_{max} = \frac{M}{4\pi H K_H t} \quad (1)$$

where M is the mass (kg) of dye released, H is a depth of water (m) over which the dye is assumed to mix vertically, K_H is the horizontal diffusivity (m^2 s^{-1}), assumed equal in x- and y-

directions, and t is the time elapsed since release (s). The maximum concentration measured during each post-release survey should fall according to Equation (1) and allow an estimate of K_H to be made.

For each dye release at Tabhaigh, we have identified the maximum concentration measured in each post-release survey (each comprised of a number of individual transects) and plotted the maximum concentration against the nominal time for that survey (typically accurate to ±15 minutes). The results show that a value of K_H = 0.1 m^2 s^{-1} is a reasonable (and generally conservative) estimate of horizontal diffusivity, in that the measured peak concentrations decrease more quickly than the theoretical values for K_H = 0.1 m^2 s^{-1} (Figure 8). These data, and all other dye studies undertaken by Mowi in recent years, suggest that a horizontal diffusivity of 0.1 m^2 s^{-1} is a reasonable estimate of short term eddy diffusion in Scotland's coastal marine environment. A similar conclusion was reached by Dale et al. (2020) following dye releases conducted in Loch Linnhe and adjacent waters.

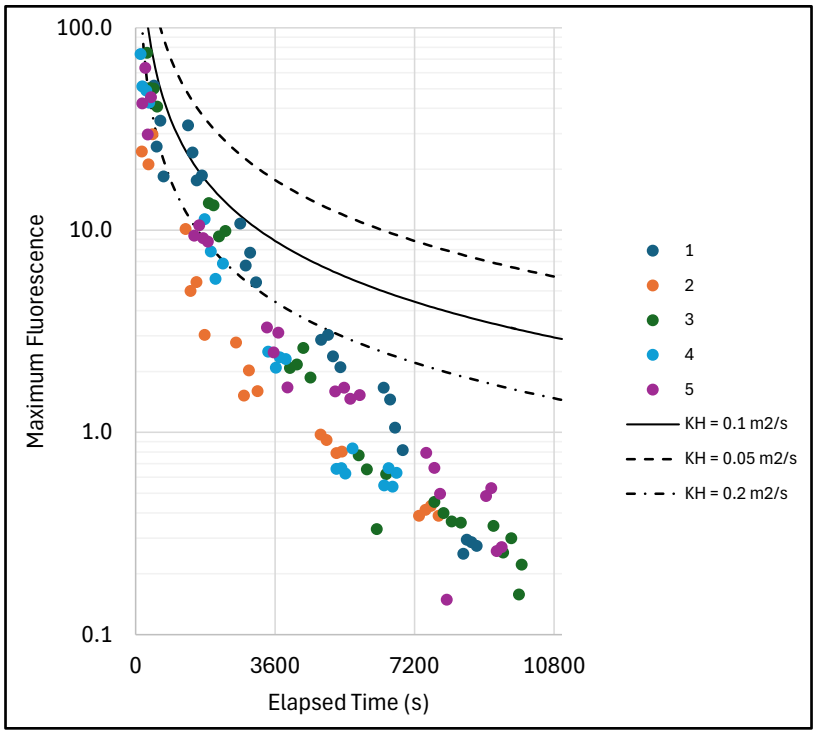

Figure 8. Maximum fluorescence (solid circles) measured following dye releases at Tabhaigh in July 2020. Five sets of releases are shown, numbered 1 – 5. The black lines indicate the theoretical rate at which the maximum concentration would fall at different horizontal diffusivities (K_H = 0.05 m^2 s^{-1}, 0.10 m^2 s^{-1} and 0.2 m^2 s^{-1}).

Most of the simulations described here were conducted using a value of K_H = 0.1 m^2 s^{-1}, the minimum horizontal diffusion given for modelling bath treatments over periods greater than half-an-hour. However, the sensitivity of the model to K_H was explored, using values of K_H = 0.05 m^2 s^{-1} and K_H = 0.2 m^2 s^{-1}.

3 RESULTS

3.1 Dispersion During Neap Tides, February 2021 (ID368)

A standard treatment of 8 x 160 m pens, with a reduced net depth of 5 m and assuming 1 pen could be treated per day at a treatment concentration of 100 µg L^{-1}, resulted in a treatment mass per pen of azamethiphos of 1021 g, a daily (24-hour) release of the same mass of 1021 g and a total treatment release of 8.17 kg over 168 hours. The dispersion of the medicine during and following treatment from Run001 (Table 4) is illustrated in Figure 9. After 24 hours, as the second treatment on day 2 was discharged, discrete patches of medicine are evident from the first treatment release from the first day. The maximum concentration at this time is about 100 µg L^{-1}, due to the release of the second treatment. After 72 hours, as the treatment is discharged, discrete patches of medicine from the previous treatment releases are still evident, but the patches of medicine have rapidly dispersed and are already down to concentrations of the same order as the EQS (0.04 µg L^{-1}). Again, the maximum concentration at this time was approximately 100 µg L^{-1}, due to the release of the fourth treatment.

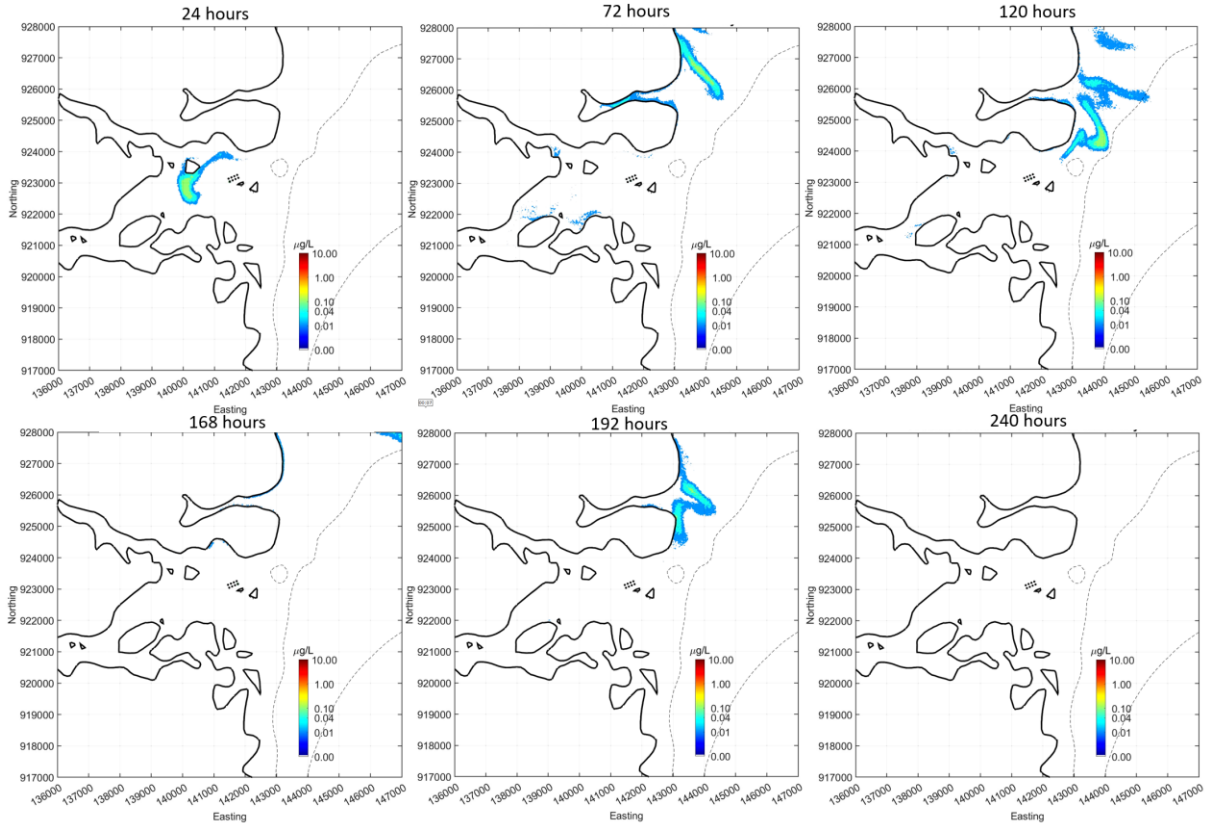

Figure 9. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 72 hours (top middle), 120 hours (top right), 168 hours (bottom left), 192 hours (bottom middle) and 240 hours (bottom right).

The treatment schedule completed after 168 hours (7 days). At this stage, the medicine released on earlier days had already dispersed Northwards. It is noticeable that dispersion of the medicine does not happen in a gradual “diffusive” manner, but is largely driven by eddies and horizontal shear in the spatially-varying velocity field, which stretches and distorts the medicine patches and enhances dispersion. Following the last treatment at 168 hours, the final

treatment patch was rapidly dispersed and concentrations rapidly fell away below the EQS (192 hrs and 240 hrs, Figure 9).

The time series of maximum concentration from this simulation is shown in Figure 10. The 8 peaks in concentration of ~100 µg L^{-1} following each treatment event over the first 7 days are evident. Following the final treatment after 168 hours, the maximum concentration fell steadily away (Figure 10). A default half-life of 134.4 hours (5.6 days) was used. The maximum concentration seventy-two hours after the final treatment (time = 240 hours) was below 0.1 µg L^{-1}, the maximum allowable concentration (MAC).

The area where the EQS of 0.04 µg L^{-1} was exceeded peaked at about 0.4 km^2 following the final treatment, but had fallen below 0.5 km^2 within 48 hours of the final treatment; by 72 hours after the final treatment, the exceeded area was close to zero (Figure 10).

These results indicate that, with a horizontal diffusion coefficient of 0.1 m^2 s^{-1}, and a medicine half-life of 134.4 h, the EQS are comfortably achieved. In the following sections, the sensitivity of the model results to the medicine half-life, diffusion coefficients and tidal state are examined.

3.2 Sensitivity to Diffusion Coefficients

The model results were tested for sensitivity to the horizontal and vertical diffusion coefficients used. The horizontal diffusion coefficient used for the standard runs was K_H = 0.1 m^2 s^{-1}. Simulations were also performed with lower and higher values of K_H, specifically K_H = 0.2 m^2 s^{-1} and K_H = 0.05 m^2 s^{-1} (Table 4). The time series of maximum concentration and area exceeding the EQS are shown in Figure 10. The time series confirm that the MAC was not exceeded after 240 hours (72 hours after the final treatment). The area limit of 0.5 km^2 was also comfortably met in all cases.

Similarly, sensitivity to the vertical diffusion coefficient, K_V, was tested (Figure 11). The model results are not particularly sensitive to the vertical diffusion rate, but increased vertical diffusion, likely in the presence of wind and/or waves, led to slightly smaller areas where the EQS was exceeded.

3.3 Sensitivity to Release Time

The baseline simulation was repeated with the time of the releases varied by up to ±6 hours, the purpose being to assess the influence, if any, of the state of the tide on subsequent dispersion. The results show some minor variability. A half-life of 134.4 hours was used in these runs which is thought to still be conservative.

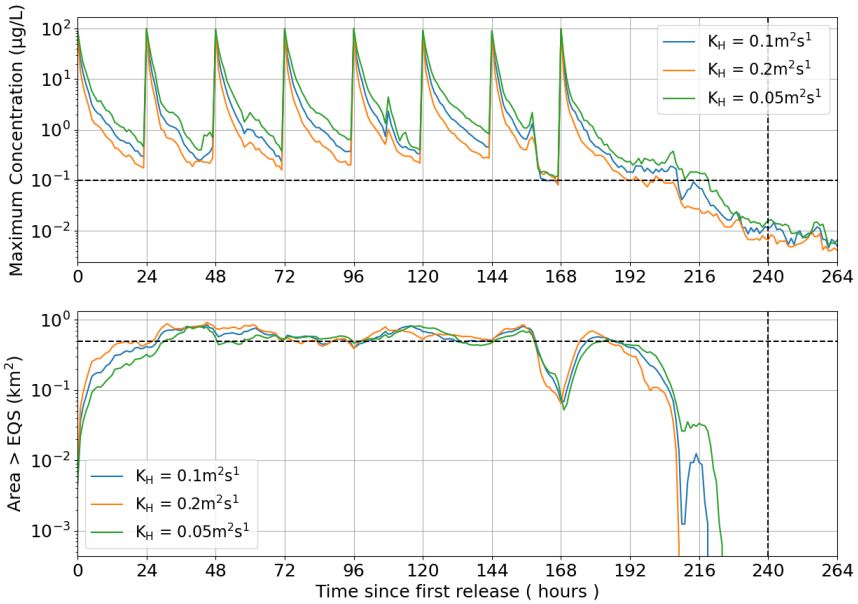

Figure 10. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient K_H ($m^2\ s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

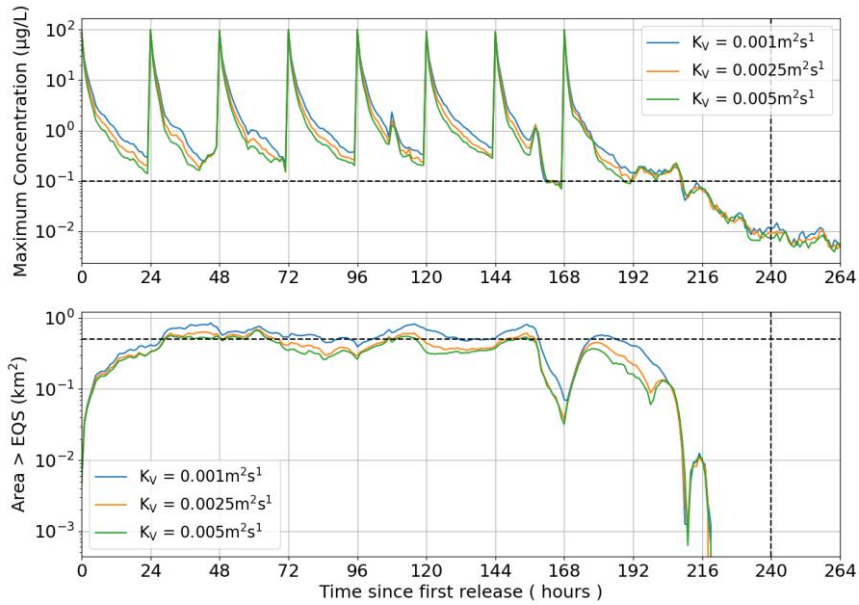

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient K_V ($m^2\ s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

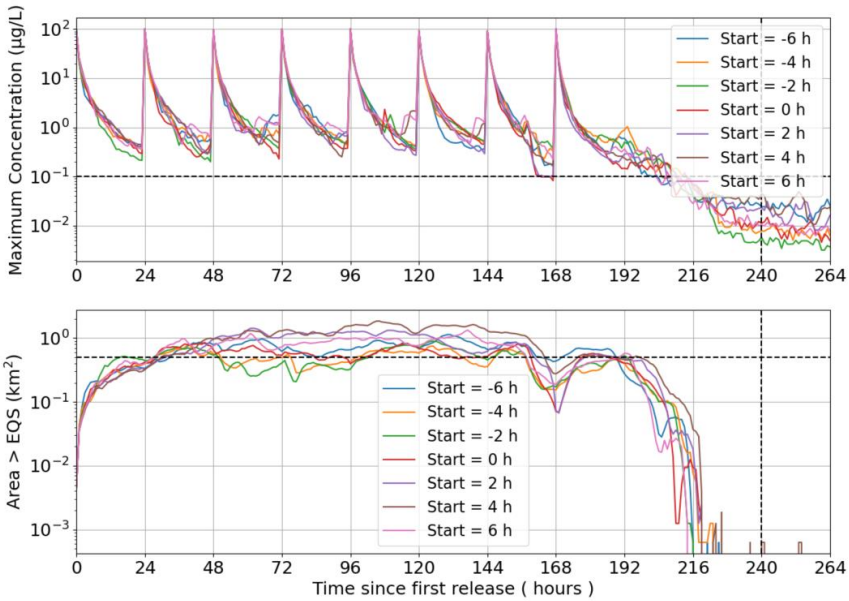

Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.4 Dispersion during Spring Tides, March 2021 (ID368)

Dispersion simulations were carried out during modelled spring tides in March 2021 (Figure 4), repeating the main set carried out for neap tides (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 1021 g of azamethiphos. For all medicine half-lives, horizontal and vertical diffusion coefficients simulated both the MAC and area EQS were achieved (Figure 13).

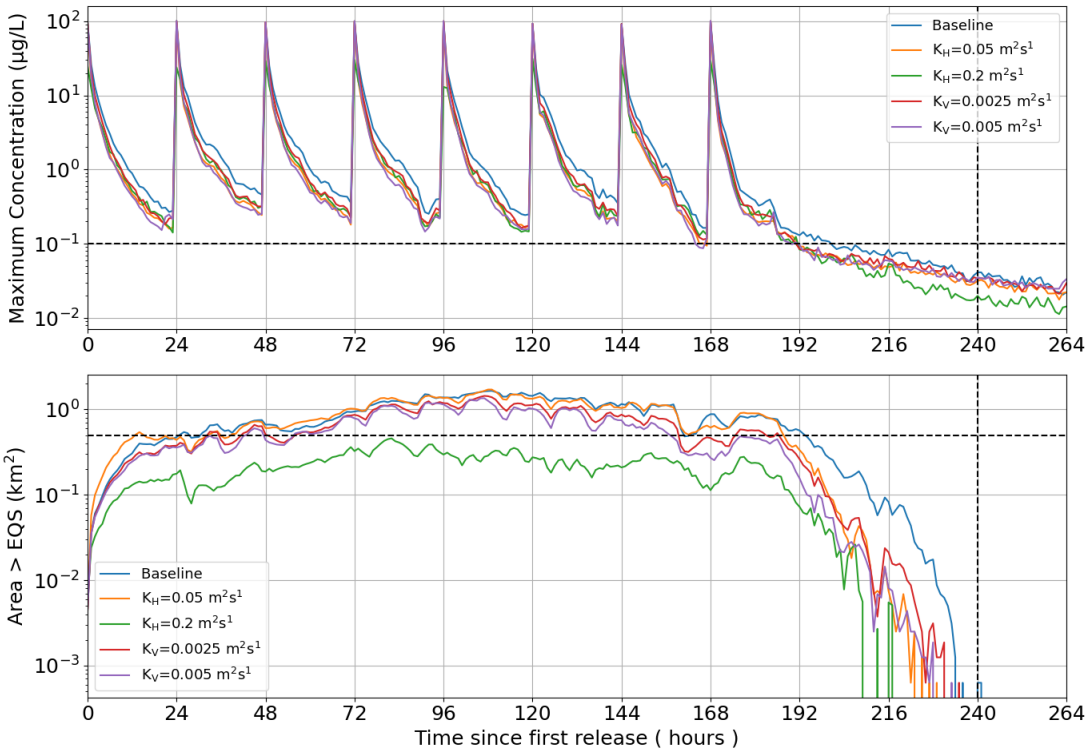

Figure 13. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient K_H ($m^2\ s^{-1}$) and vertical diffusion coefficient K_V ($m^2\ s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.5 Dispersion During Neap Tides, January 2021 (ID363)

A further set of dispersion simulations during modelled neap tides in January 2021 were carried out (Figure 14), repeating the main set carried out for neap tides in February 2021 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 1021 g of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved, aside from a marginal fail when a very low horizontal diffusivity of K_H=0.05 $m^2\ s^{-1}$ was used.

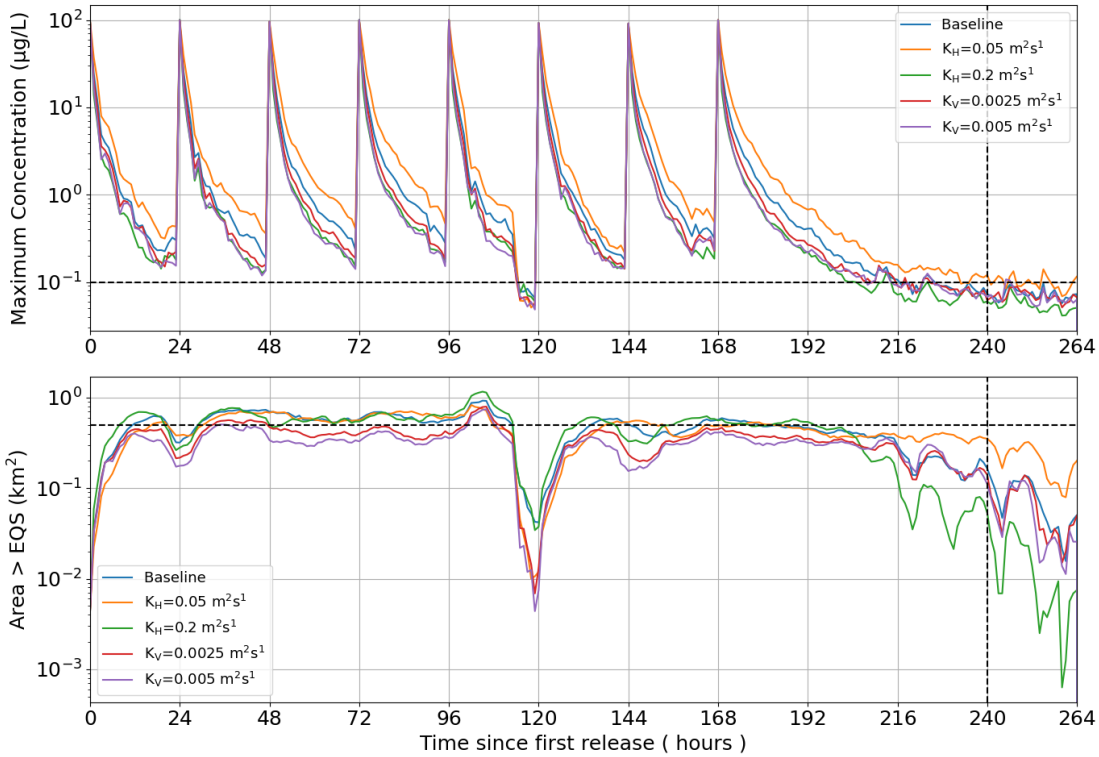

Figure 14. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, ninth and tenth set of model runs (Table 4). The model was run at neap tides from January 2021, horizontal diffusion coefficient K_H ($m^2 s^{-1}$) and vertical diffusion coefficient K_V ($m^2 s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.6 Azamethiphos 3-Hour EQS

The 3-hour mixing zone is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 6.67 cm s^{-1} was used from ID368 (Table 5) which was thought to be a representative value for the surface 0 – 5 m layer at Tabhaigh. The parameter values used in the calculation of the 3-hour mixing zone ellipse area are shown in Table 5.

The time series of the areas where the 3-hour EQS of 250 ng L^{-1} is exceeded for each individual pen treatment at neap tide (first release on 15th February 2021) are shown in *Figure 15*. For each treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.105 km^2) after 3 hours. The peak concentration of 100 µg L^{-1} decreased to less than 10 µg L^{-1} within the 3-hour period.

For spring tide releases (first release on 10th March 2021), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 16). As for the neap tide simulation, the peak concentrations fell by an order of magnitude within the three hours.

This demonstrates that the discharge quantity of 1021 g of azamethiphos from each of the eight 160 m pens at Tabhaigh should not breach the 3-hour EQS.

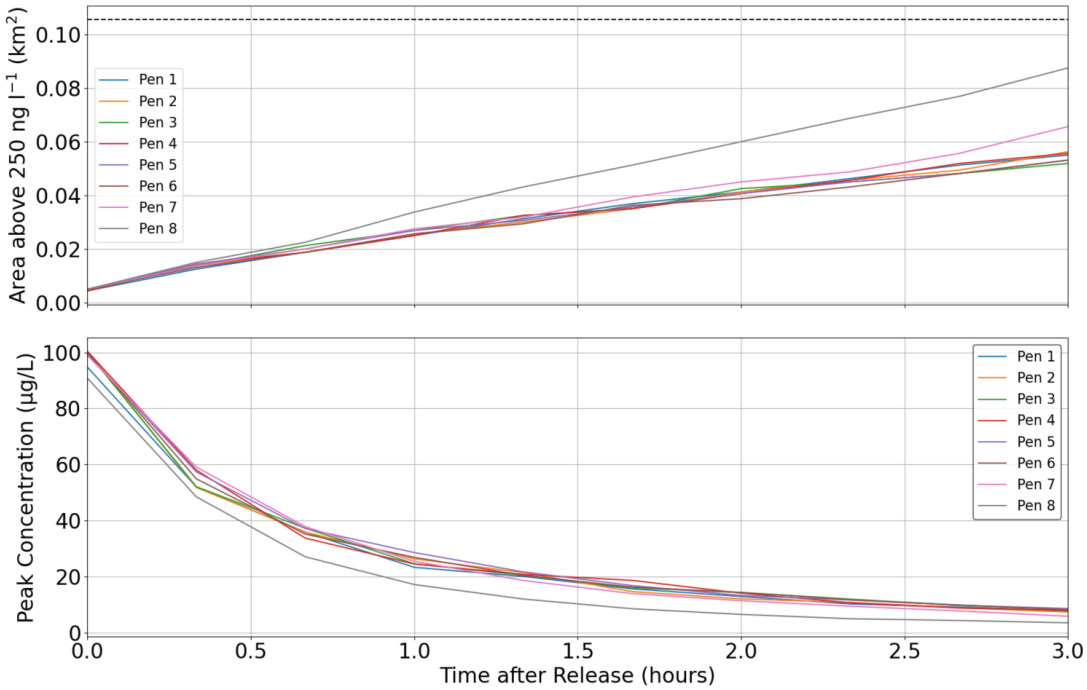

Figure 15. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

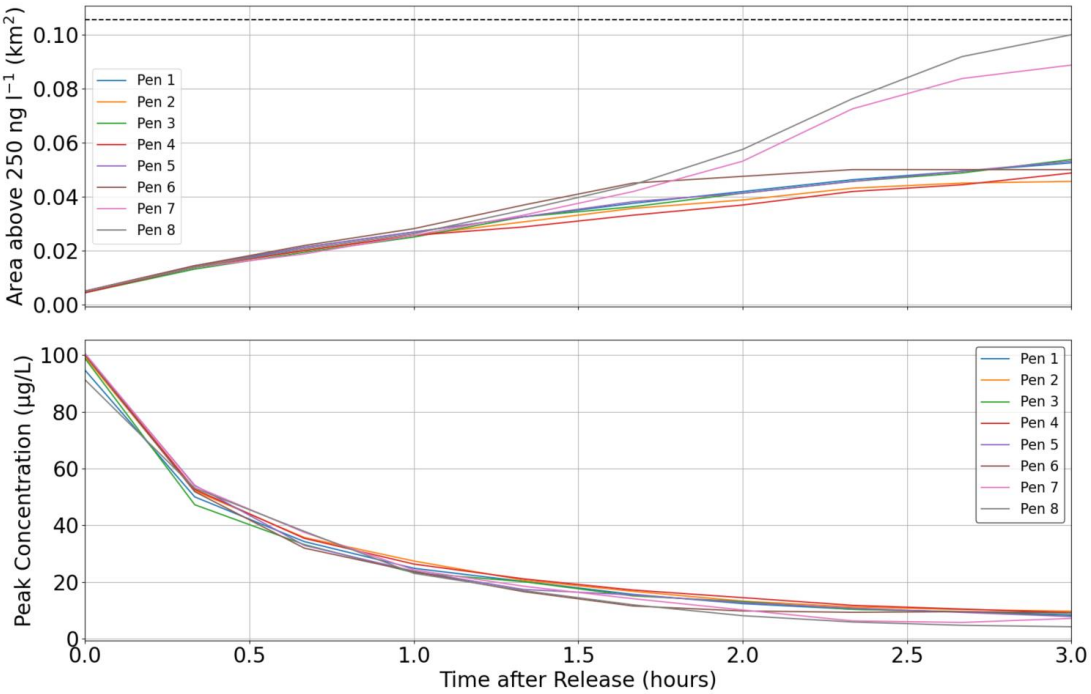

Figure 16. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area indicated (---).

3.7 Interactions with identified features

Figure 17 shows the maximum peak concentrations of Azamethiphos every hour within the identified special feature area at spring tide for a 5 m layer above the seabed following treatment at Tabhaigh. The concentrations shown during spring tide are minimal, with maximum concentrations well below the 3-hour (0.25 µg L^{-1}) and the 72-hour (0.10 µg L^{-1}) MAC for the whole duration of the simulation.

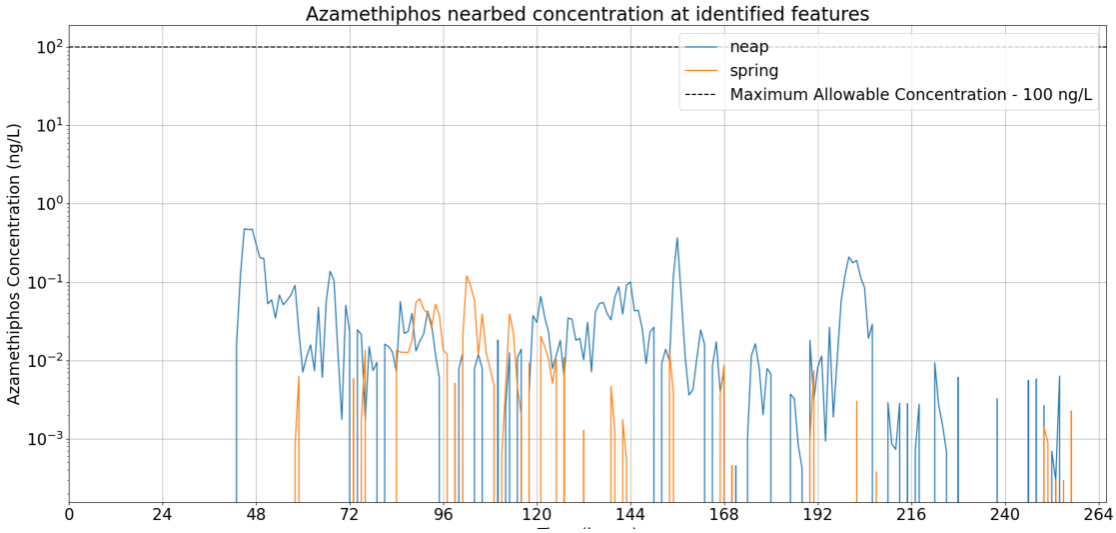

Figure 17. Maximum peak concentrations over neap and spring tides for identified features. The MAC at 72 hours of 0.1 µg L^{-1} is indicated by the horizontal dashed line.

3.8 Deltamethrin 6-Hour EQS

The 6-hour mixing zone for Deltamethrin is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 6.67 cm s^{-1} was used from ID368 (Table 1) which was thought to be a representative value for the surface 0 – 5 m layer at Tabhaigh. The parameter values used in the calculation of the 6-hour mixing zone ellipse area are shown in Table 7.

The time series of the areas where the 6-hour EQS of 6 ng L^{-1} is exceeded for each individual pen treatment at neap tide (first release on 15th February 2021) are shown in Figure 18. For each treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.279 km^2) after 6 hours. The peak concentration of 2 µg L^{-1} decreased to less than 0.1 µg L^{-1} within the 6-hour period.

For spring tide releases (first release on 10th March 2021), the area where concentrations exceeded the 6-hour EQS also complied with the allowable area (Figure 19). As for the neap tide simulation, the peak concentrations fell by an order of magnitude within the three hours.

This demonstrates that the discharge quantity of 20.4 g of deltamethrin from each of the eight 160 m pens at Tabhaigh should not breach the 6-hour EQS.

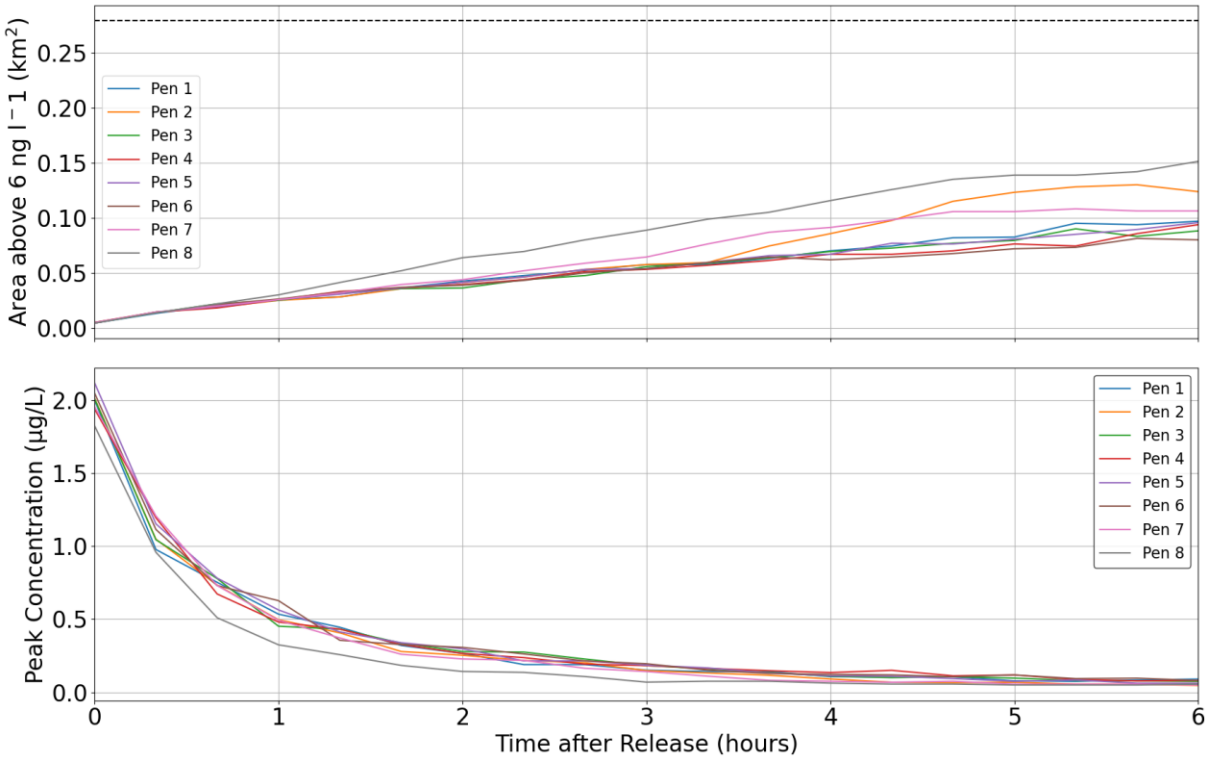

Figure 18. Time series of the area exceeding the 6-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 6 hours following release at neap tide. The 6-hour mixing zone area is indicated (---).

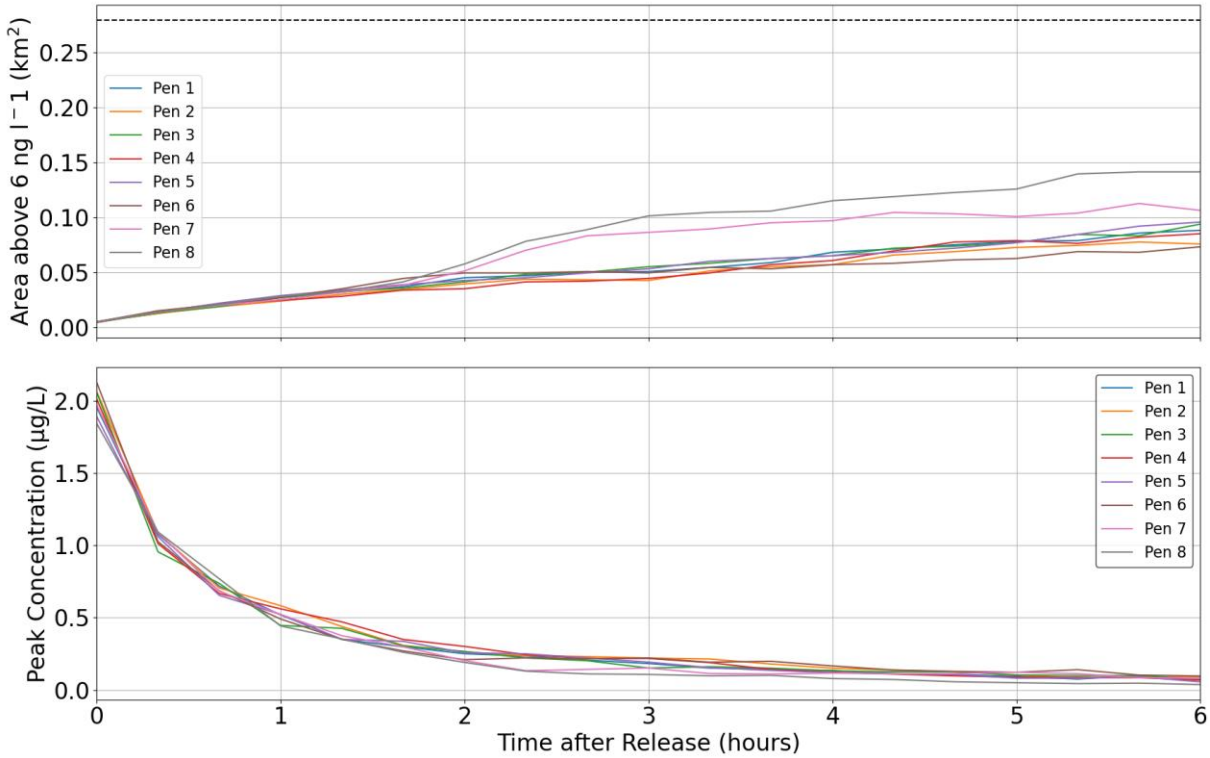

Figure 19. Time series of the area exceeding the 6-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 6 hours following release at spring tide. The 6-hour mixing zone area indicated (---).

4 SUMMARY AND CONCLUSIONS

A total of 21 dispersion simulations have been performed to assess whether bath treatments at Tabhaigh salmon farm will comply with pertinent EQS. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1021 g of azamethiphos for treatment, resulting in a total discharge over 7 days of 8.17 kg and separately 0.1632 kg of deltamethrin over 7 days. Simulations were performed separately for modelled neap and spring tides, and the sensitivity of the results to key model parameters was tested. Results are summarised in Table 7.

Table 7. Summary of Results

Site Details	
Site Name:	Tabhaigh
Site Location:	Loch Erisort
Peak Biomass (T):	2,500
Pen Details	
Number of Pens:	8
Pen Circumference (m):	160
Working Depth (m):	20 and 15
Pen Group Configuration:	2 x 4
Azamethiphos Consent	
Recommended 3-hour (g):	1021
Recommended 24-hour (g):	1021
Deltamethrin Consent	
Recommended 3-hour (g)	20.4

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 1021 g of azamethiphos or 20.4g of deltamethrin, should consistently comply with the relevant EQS. The peak concentration of azamethiphos during the baseline simulation after 240 hours (72 hours after the final treatment) was less than 0.1 µg L^{-1}, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg L^{-1} was substantially less than the allowable 0.5 km^2. In all simulations performed, including sensitivity testing, the EQS and MAC criteria were met, with the exception of the horizontal diffusivity run (Run019) with K_H=0.05 m^2 s^{-1}. This diffusivity value is considered to be very low. For the simulations during spring tides, greater dispersion meant that the MAC and EQS were met very comfortably. Peak concentrations near the seabed at the identified special feature area (SEPA, 2023a) were found to be consistently less than the 3-hour and 72-hour MAC over the full treatment simulation. Therefore, it is believed that the requested daily quantity of 1021 g of azamethiphos or 20.4 g of deltamethrin and can be safely discharged at Tabhaigh without breaching the MAC or EQS.

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