



Medicine Dispersion Modelling Tabhaigh East, Loch Erisort

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at the proposed Tabhaigh East 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 1222 g of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) resulting in a daily release of 1222 g and a total discharge over 7 days of 9.78 kg for azamethiphos or 22 g of deltamethrin for treatment, and 0.176 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 1222 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 $0.1 \mu\text{g L}^{-1}$, the maximum allowable concentration, and the area where concentrations exceeded the EQS of $0.04 \mu\text{g L}^{-1}$ was substantially less than the allowable 0.5 km^2 . 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 East
Site Location:	Loch Erisort
Peak Biomass (T):	2,075
Pen Details	
Number of Pens:	8
Pen Circumference (m):	160
Working Depth (m):	15 & 20
Pen Group Configuration:	2 x 4
Azamethiphos Consent	
Recommended 3-hour (g):	1222
Recommended 24-hour (g):	1222
Deltamethrin Consent	
Recommended 6-hour (g)	22

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 establish a consent of topical sea lice veterinary medicines at the proposed marine salmon farm Tabhaigh East, 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, 2023).

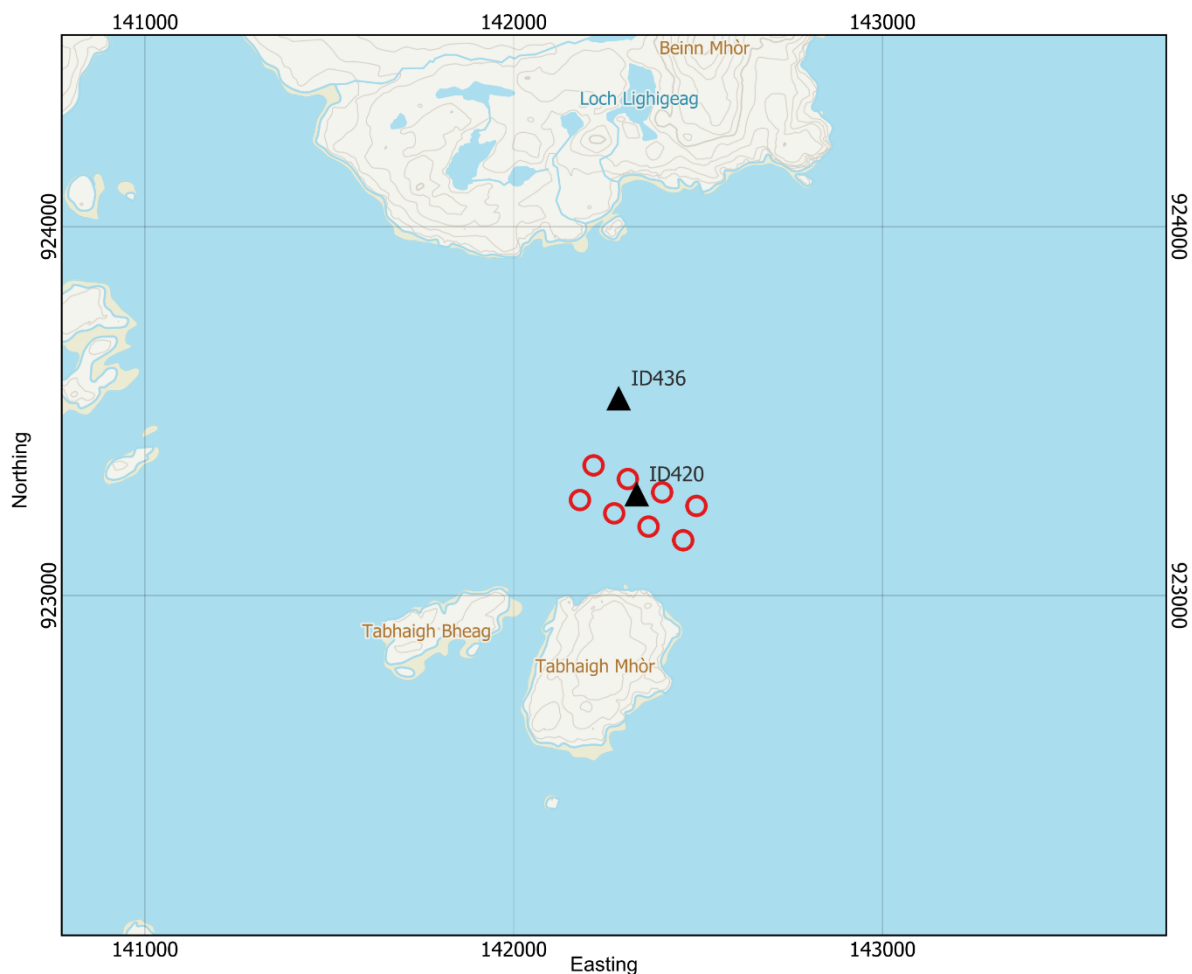


Figure 1. Location of proposed Tabhaigh East salmon farm and the location of the ADCP deployments (▲) relative to the proposed pen positions (○).

1.1 Site Details

The site is situated toward the mouth of Loch Erisort, immediately north of the island Tabhaigh Mhòr (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	ID420	ID436
Site:	Tabhaigh East	Tabhaigh East
Current Meter Position:	142334E 923275N	142285E 923535N
Depth of Deployment Position (m):	51.77	66.58
Surface Bin Centre Height Above Bed (m):	42.55	56.71
Middle Bin Centre Height Above Bed (m):	33.55	48.71
Bottom Bin Centre Height Above Bed (m):	3.55	3.71
Duration of Record (days):	98.74	89.61
Start of Record:	28/06/2023 17:00	29/02/2024 17:00
End of Record:	05/10/2023 10:40	29/05/2024 07:40
Current Meter Averaging Interval (min):	20	20
Magnetic Correction to Grid North:	-3.72	-3.72

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, 2025), and is only summarised here.

For the hydrodynamics, the FVCOM model was used. 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 momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure submodels. The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is presented using generalized terrain-following coordinates. The 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.

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. Further details of the FVCOM model and simulations are given in Mowi (2025).

For the particle tracking component, Mowi's in-house model UnPTRACK (Gillibrand, 2024) was used. The model used the hydrodynamic flow fields from the FVCOM model simulations. 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 East 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 a previous mesh used for modelling medicine dispersion in a neighbouring Loch in the Southeast of the Isle of Lewis (Figure 2). Model resolution was enhanced in the Loch Erisort region particularly around the proposed site at Tabhaigh Mor (Figure 3). The spatial resolution of the model varied from 33 m in some inshore waters to 400 m along the open boundary. The model consisted of 37,604 nodes and 71,795 triangular elements. Model bathymetry was taken from the European Marine Observation and Data Network (EMODnet), supplemented by a multibeam survey undertaken in May 2023 (Figure 3).

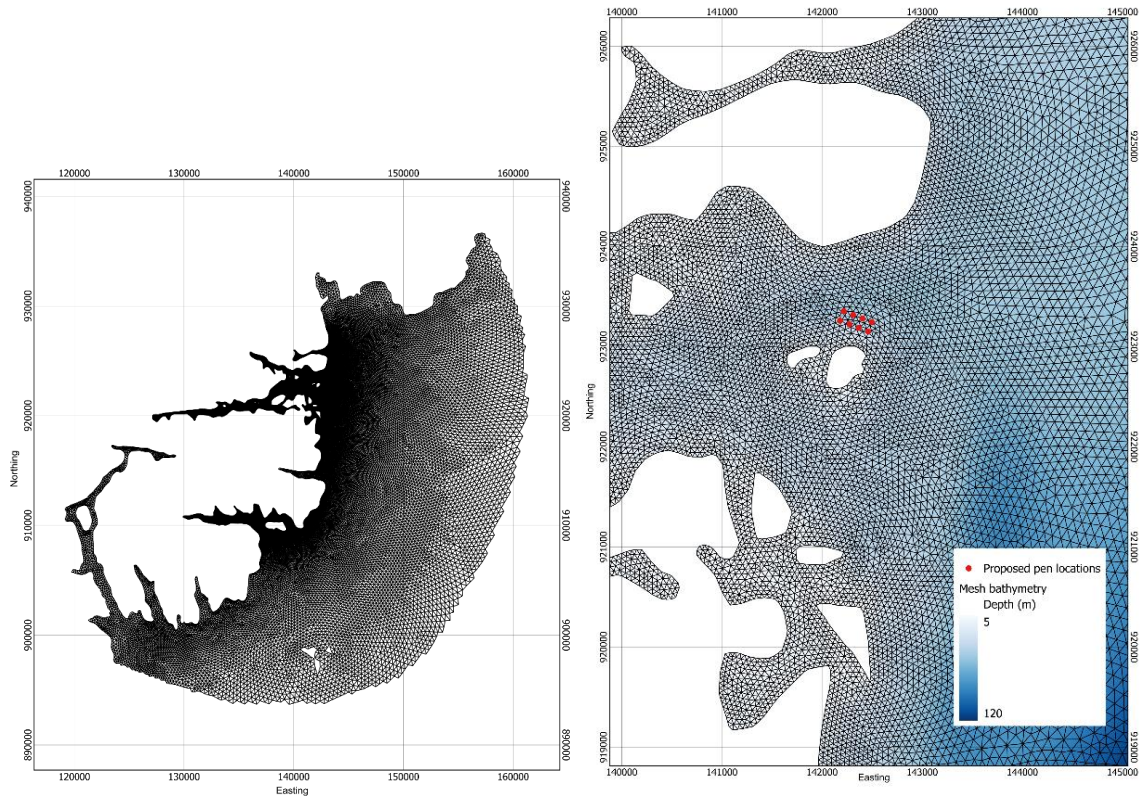
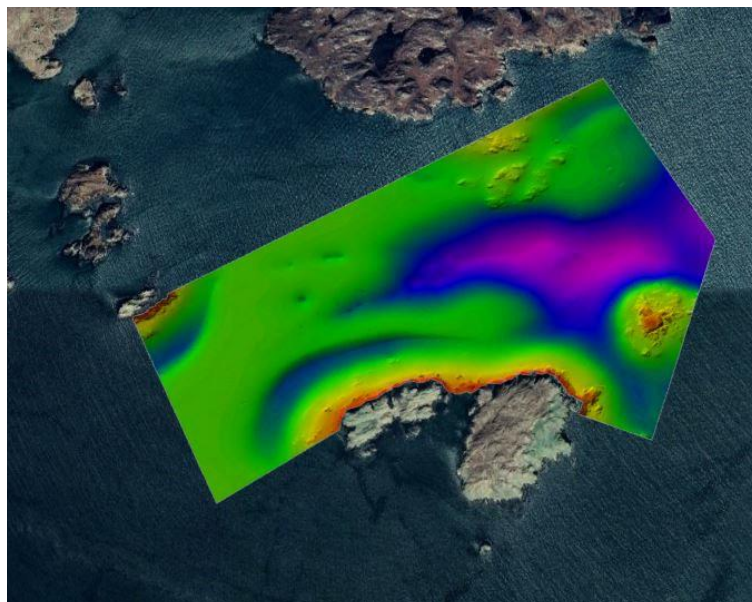


Figure 2. The mesh and domain of the modelling study (left) and the mesh around the proposed site (right).



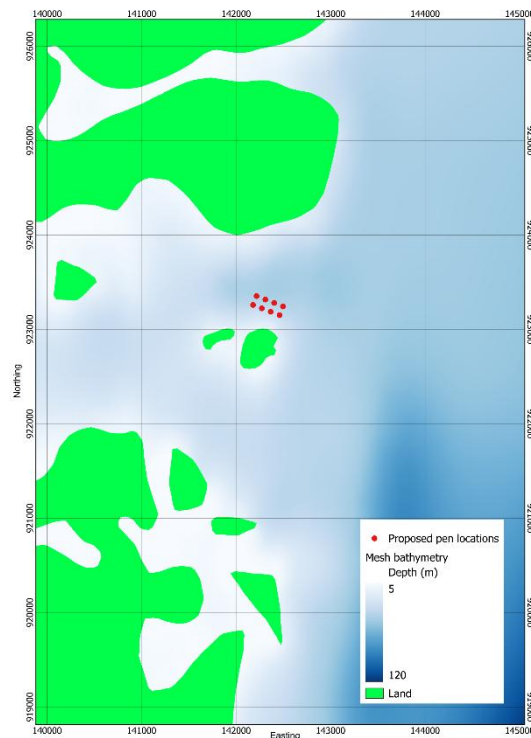


Figure 3. Multibeam bathymetry (top) and water depths (m, right) in the area around the proposed Tabhaigh site (bottom). The proposed pen locations are indicated (●).

The model was forced along its open boundary by time series of sea surface height (SSH) at each boundary node for the relevant simulation periods; FVCOM appears to perform better with time series boundary forcing than when tidal constituents are used. The SSH time series were generated using the RiCOM hydrodynamic model (Walters and Casulli, 1998; Gillibrand et al., 2016) on the ECLH grid (Price et al., 2016), which was, in turn, forced by eight tidal constituents (O_1 , K_1 , Q_1 , P_1 , M_2 , S_2 , N_2 , K_2) taken from the full Scottish Shelf model (SSM). Wind speed and direction data for the simulation periods were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset.

Stratification is expected to be moderate in this location and the model was run in 3D baroclinic mode. Ten layers in the vertical (eleven sigma levels) were used in the simulations, with layers concentrated near the surface and seabed (Mowi, 2025). Climatological river flow data were used, taken from the Marine Scotland Scottish Shelf Model climatology (De Dominicis et al., 2018). Nine freshwater discharges into the model domain were specified, with two going into Loch Leurbost and Loch Erisort.

Full details of the calibration and validation of the hydrodynamic model are given in the Tabhaigh East Hydrodynamic Model Description (Mowi, 2025).

2.2 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the UnPTRACK model (Gillibrand, 2024), 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 $120 \mu\text{g L}^{-1}$, with a total mass of 9.78 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.* 162,976 numerical particles in total, each particle representing 60 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 50 m x 50 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 ($\mu\text{g L}^{-1}$) 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 2023 (ID420) (Figure 4). A further simulation was performed over neap tides in March 2024 (ID436) to confirm the adequacy of dispersion during the weakest tides (Figure 5).

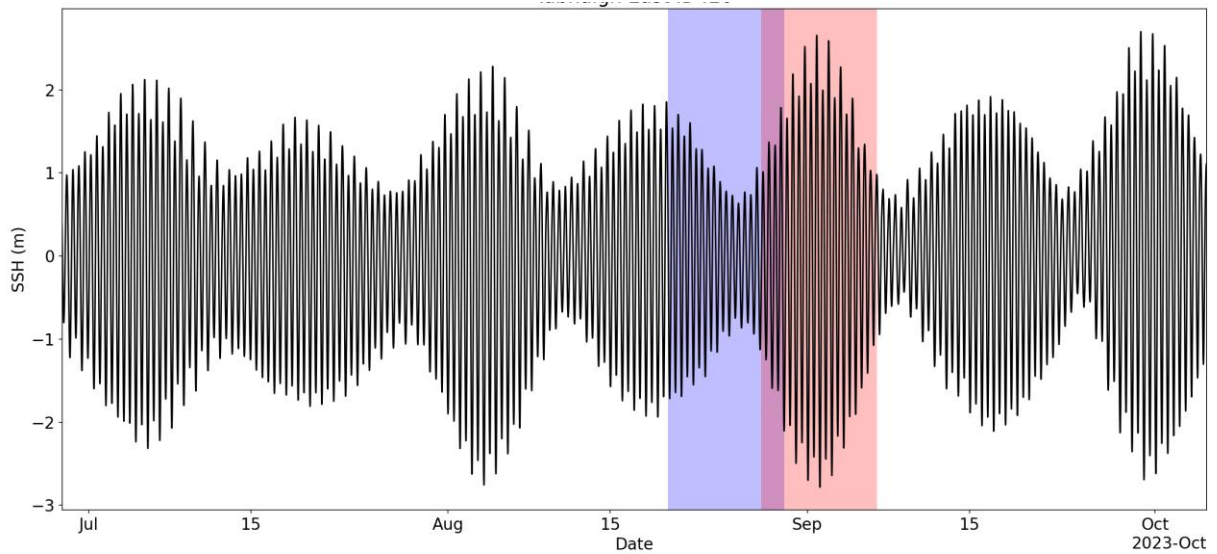


Figure 4. Sea surface height (SSH) at Tabhaigh East from 28th June 2023 – 5th October 2023 (ID420). Dispersion simulations were performed over periods of neap tides (blue, start day 20th August 2023) and spring tides (red, start day 28th August 2023).

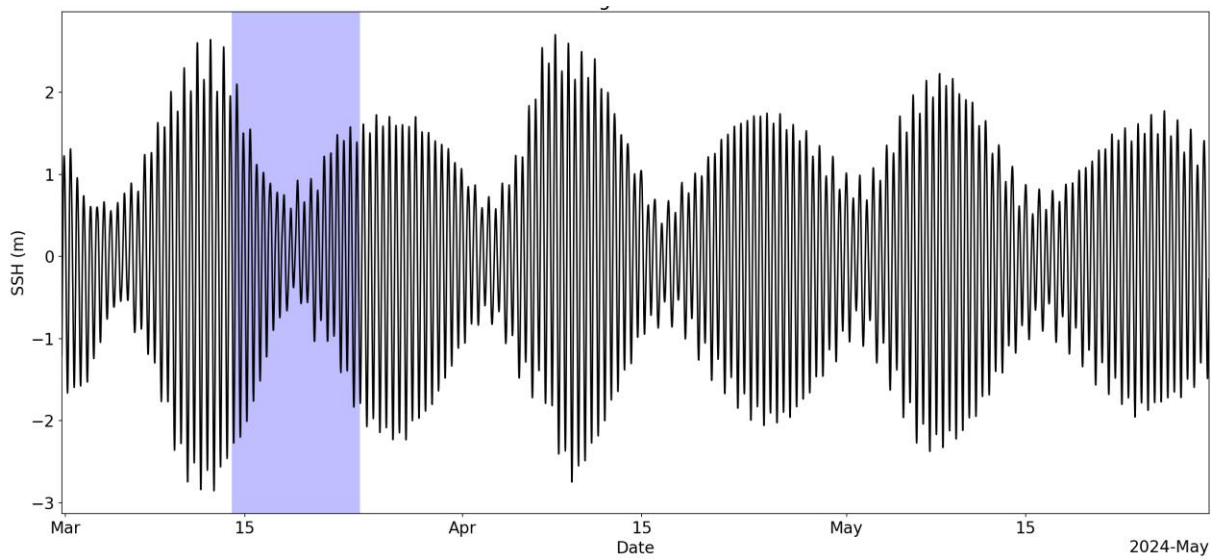


Figure 5. Sea surface height (SSH) at Tabhaigh East from 29th February 2024 – 29th May 2024 (ID436). Dispersion simulations were performed over periods of neap tides (blue, start day 14th March 2024).

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.

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 5.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (g)	Release Time (hr)
1	142217	923353	5	1222	0
2	142180	923259	5	1222	24
3	142310	923316	5	1222	48
4	142273	923223	5	1222	72
5	142403	923280	5	1222	96
6	142366	923187	5	1222	120
7	142496	923243	5	1222	144
8	142460	923150	5	1222	168

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

Set	Run No.	T _{1/2} (h)	K _H	K _V	Start Time
Neap Tides, Start day = 54 (20th August 2023, ID420)					
Baseline	1	134.4	0.1	0.001	00:00
Sensitivity	2	134.4	0.05	0.001	00:00
Spring Tides, Start day = 62 (28th August 2023, ID420)					
Baseline	3	134.4	0.1	0.001	00:00
Sensitivity	4	134.4	0.05	0.001	00:00
Neap Tides, Start day = 15 (14th March 2024, ID436)					
Baseline	5	134.4	0.1	0.001	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, 2023). 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 8.28 cm s⁻¹ was used from ID420 (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})	0.0828
Area of 160m pen (km^2)	0.001446
Distance from shore (km)	0.160
Mean water depth (m)	51.8
Treatment Depth (m)	5
Mixing zone ellipse area (km^2)	0.13085961

For the 3-hour EQS assessment, the baseline runs for neap and spring tides (Runs 1 and 3 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 an 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 $10 \text{ m} \times 10 \text{ m}$ grid (rather than a $50 \text{ m} \times 50 \text{ m}$ grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

2.5 Deltamethrin 6-Hour EQS

Deltamethrin dispersion was modelled using the BathAuto Excel spreadsheet. The same current data from ID420, was used as input to the spreadsheet, and the same treatment depth of 5 m. The completed spreadsheet is included with the application files.

3 RESULTS

3.1 Dispersion During Neap Tides, August 2023 (ID420)

A standard treatment of $8 \times 160 \text{ m}$ pens, with a reduced net depth of 5 m and assuming 1 pen could be treated per day at a treatment concentration of $120 \text{ } \mu\text{g L}^{-1}$, resulted in a treatment mass per pen of azamethiphos of 1222 g, a daily (24-hour) release of the same mass of 1222 g and a total treatment release of 9.78 kg over 168 hours. The dispersion of the medicine during and following treatment from Run1 (Table 4) is illustrated in Figure 6. 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 $120 \text{ } \mu\text{g L}^{-1}$, 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 ($0.04 \text{ } \mu\text{g L}^{-1}$). Again, the maximum concentration at this time was approximately $120 \text{ } \mu\text{g L}^{-1}$, due to the release of the fourth treatment.

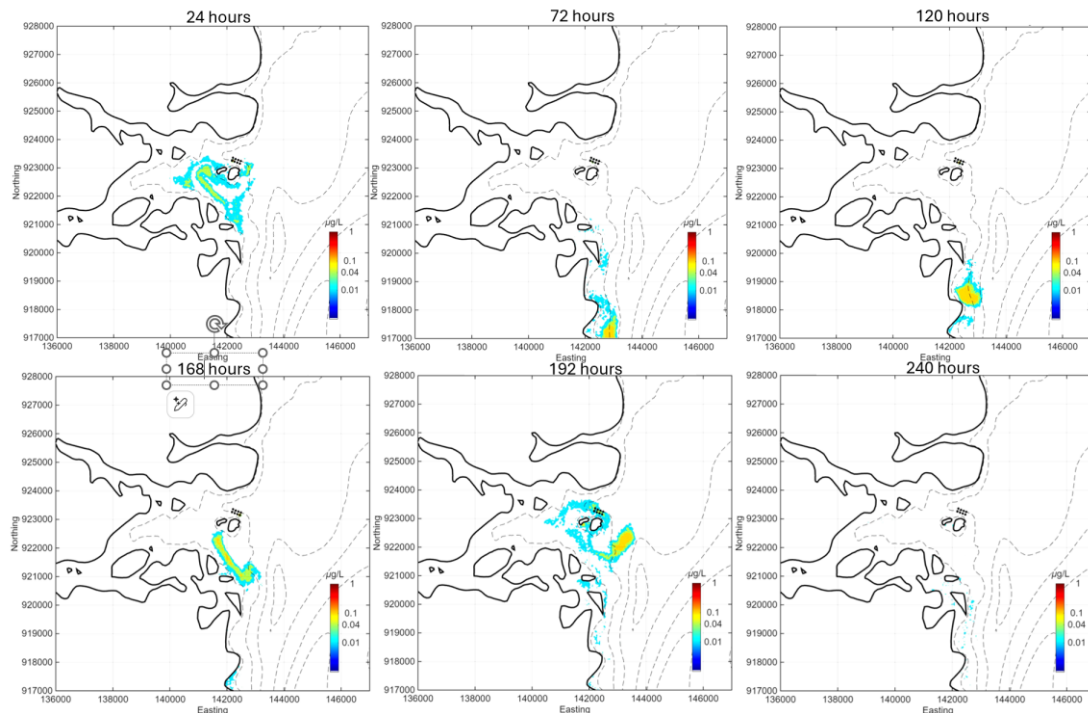


Figure 6. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 72 hours (top middle), 120 hours (top right), 168 hours (bottom left), 192 hours (bottom middle) and 240 hours (bottom right).

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 (240 hrs, Figure 6).

The time series of maximum concentration from this simulation is shown in Figure 7. The 8 peaks in concentration of $\sim 120 \mu\text{g L}^{-1}$ 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 7). 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 $0.1 \mu\text{g L}^{-1}$, the maximum allowable concentration (MAC).

The area where the EQS of $0.04 \mu\text{g L}^{-1}$ was exceeded peaked at about 0.5 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 7).

These results indicate that, with a horizontal diffusion coefficient of $0.1 \text{ m}^2 \text{ s}^{-1}$, 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 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 $K_H = 0.1 \text{ m}^2 \text{ s}^{-1}$. Simulations were also performed with a lower value of K_H , specifically $K_H = 0.05 \text{ m}^2 \text{ s}^{-1}$ (Table 4). The time series of maximum concentration and area exceeding the EQS are shown in Figure 7. The time series confirm that the MAC was exceeded for only 2 hours after 240 hours (72 hours after the final treatment). The area limit of 0.5 km^2 was also comfortably met in all cases.

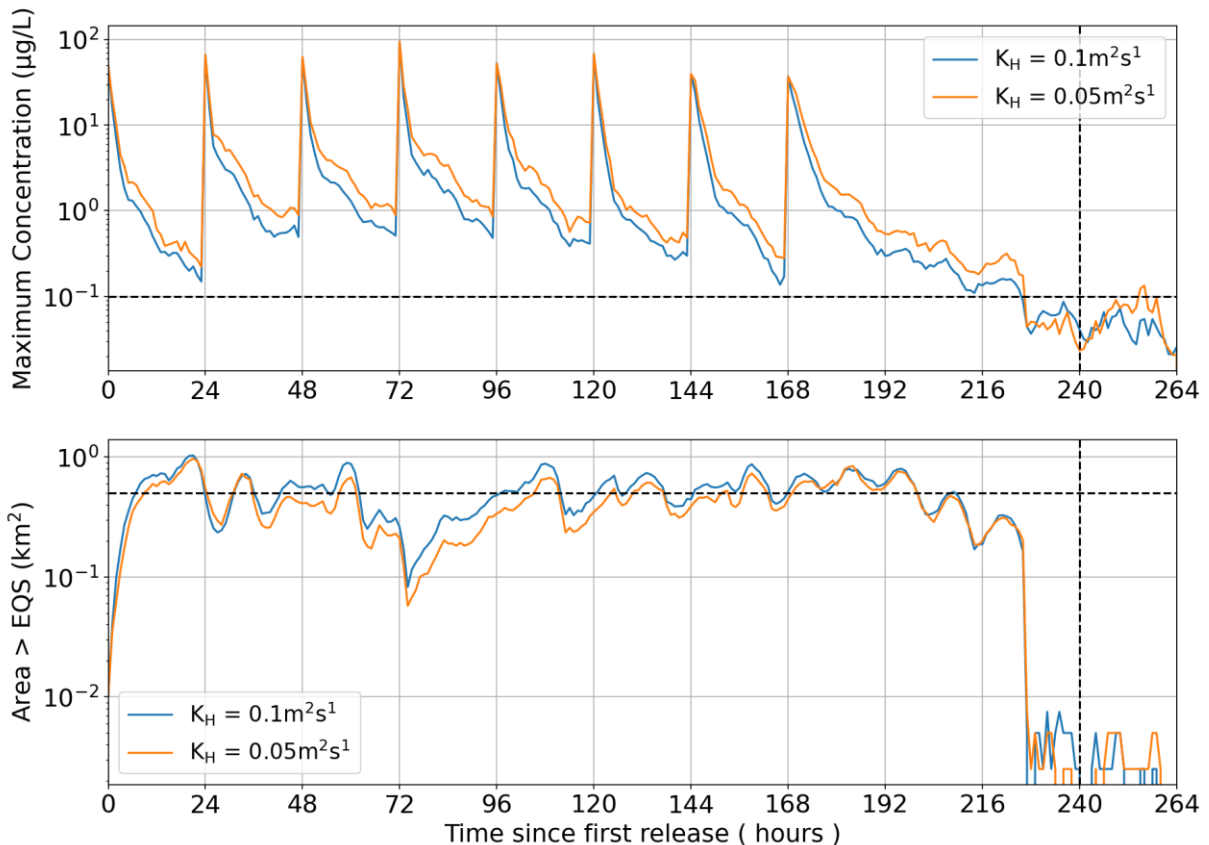


Figure 7. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient K_H ($\text{m}^2 \text{ s}^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.3 Dispersion during Spring Tides, August - September 2023 (ID420)

Dispersion simulations were carried out during modelled spring tides in August - September 2023 (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 1222 g of azamethiphos. For all horizontal diffusion coefficients simulated both the MAC and area EQS were achieved (Figure 8).

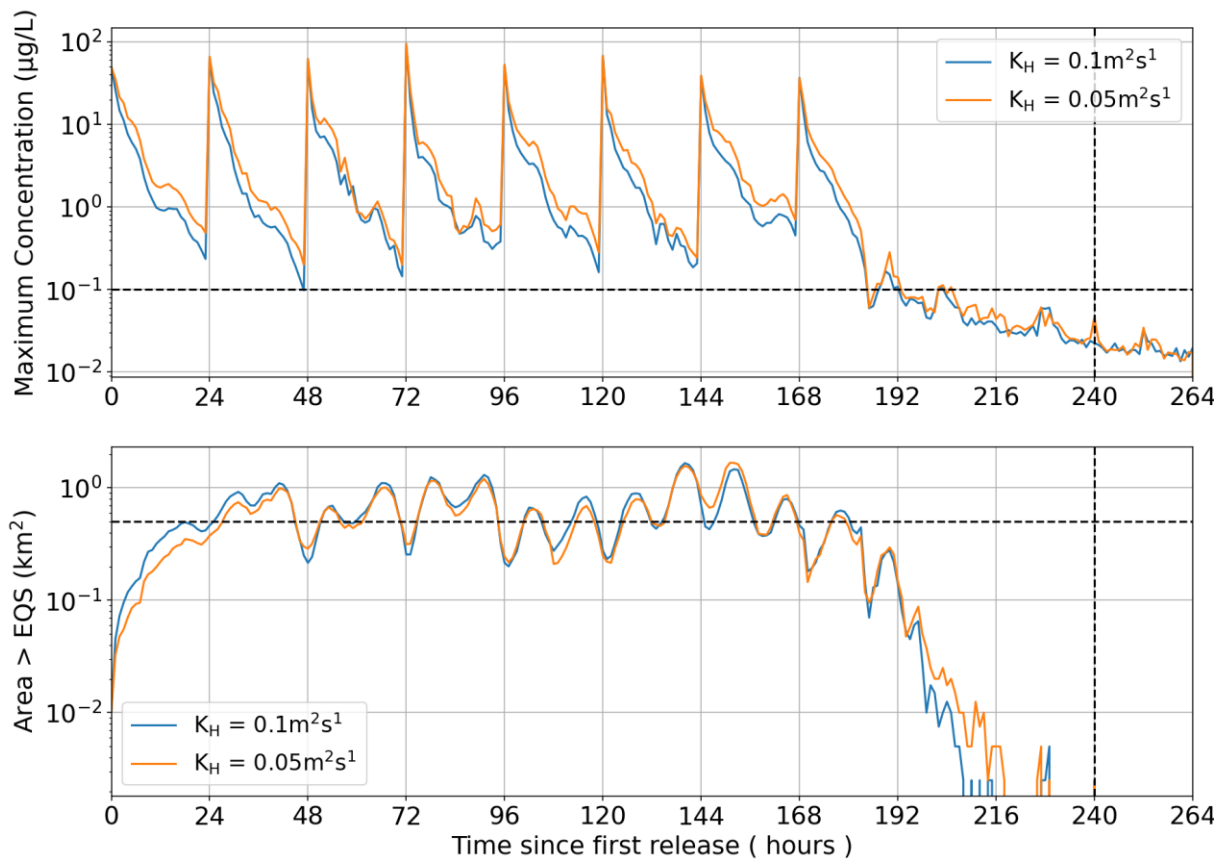


Figure 8. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the third and fourth model runs (Table 4). The model was run at spring tides with varying horizontal diffusion coefficient K_H ($\text{m}^2 \text{ s}^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of $0.1 \mu\text{g L}^{-1}$ and 0.5 km^2 are indicated by the horizontal dashed lines.

3.4 Dispersion During Neap Tides, March 2024 (ID436)

A further dispersion simulation during modelled neap tides in March 2024 was carried out (Figure 9), repeating the first set carried out for neap tides in August 2023 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 1222 g of azamethiphos. The MAC and area EQS were comfortably achieved.

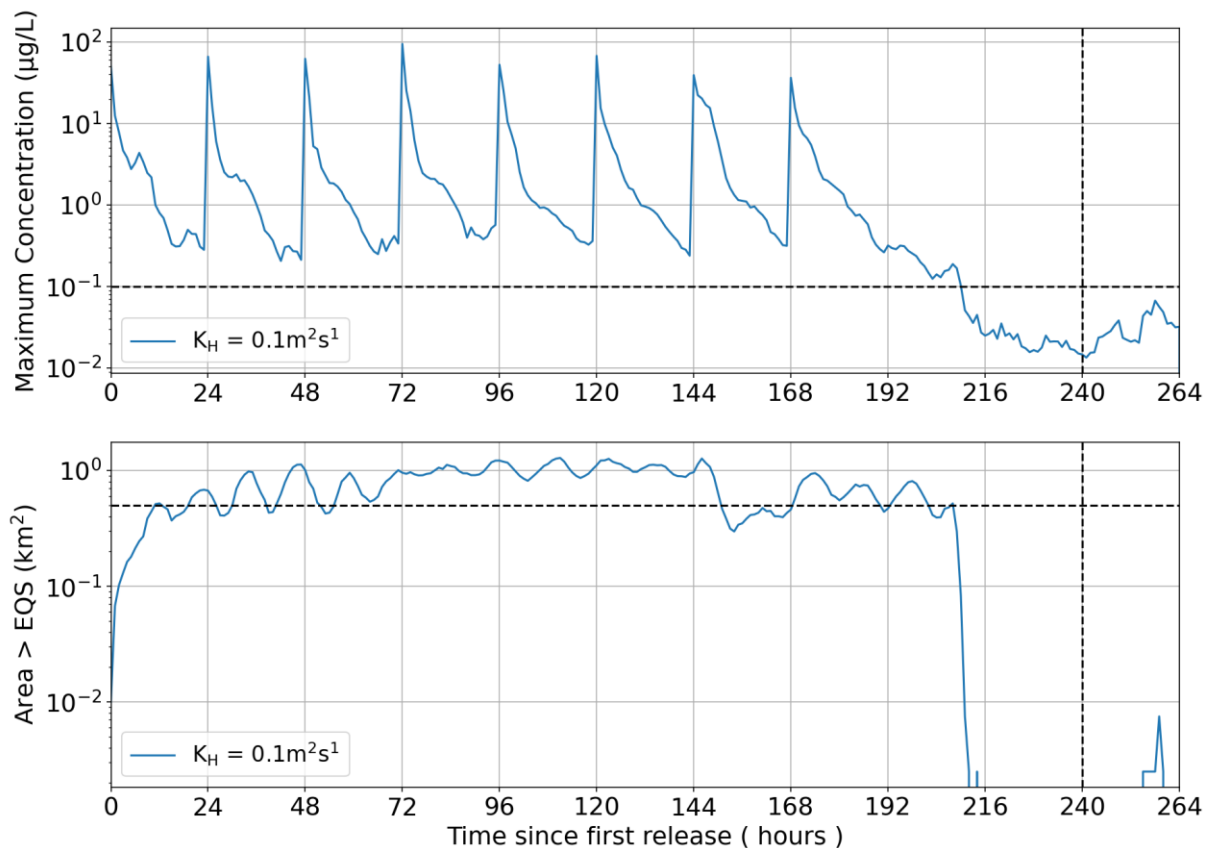


Figure 9. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth model run (Table 4). The model was run at neap tides from March 2024. The MAC and area limit 72 hours after the final treatment (Time = 240 h) of $0.1 \mu\text{g L}^{-1}$ and 0.5 km^2 are indicated by the horizontal dashed lines.

3.5 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 8.28 cm s^{-1} was used from ID420 (Table 5) which was thought to be a representative value for the surface 0 – 5 m layer at Tabhaigh East. 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 20th August 2023) are shown in Figure 10. For a treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.131 km^2) after 3 hours.

For spring tide releases (first release on 28th August 2023), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 10).

This demonstrates that the discharge quantity of 1222 g of azamethiphos from pens at Tabhaigh East should not breach the 3-hour EQS.

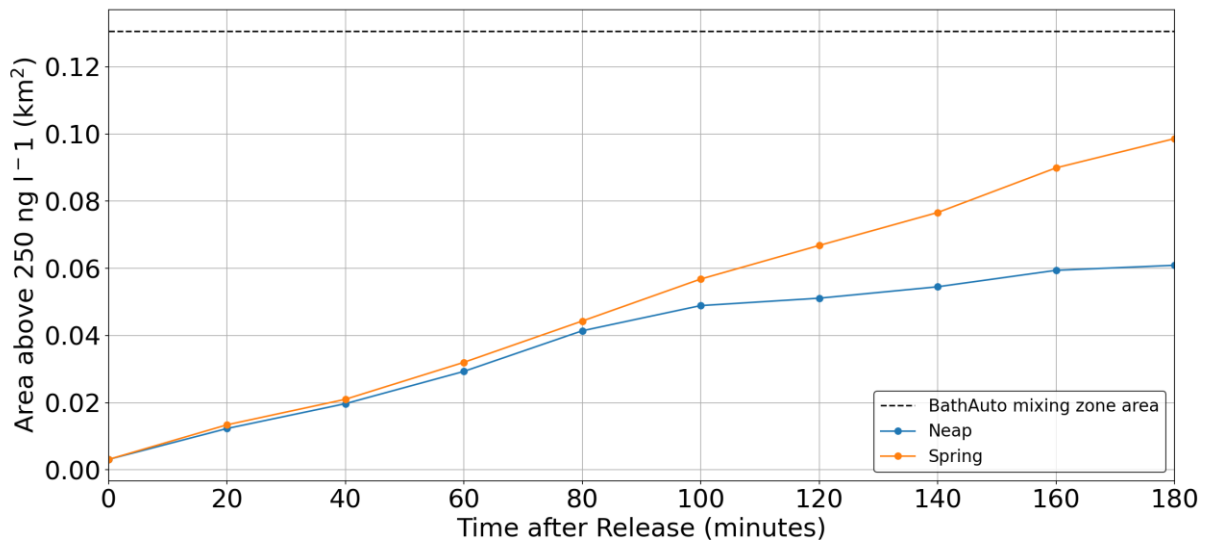


Figure 10. Time series of the area exceeding the 3-hour EQS for an individual pen treatment during the 3 hours following release at neap and spring tides. The 3-hour mixing zone area is indicated (---).

3.6 Deltamethrin 6-Hour EQS

The conservative BathAuto excel spreadsheet, using input data from the ID420 deployment, was utilised to calculate a maximum consentable quantity of Deltamethrin. The results gave a permitted Deltamethrin mass of 22 g, which allows for 1 pen to be treated every 6 hours.

4 SUMMARY AND CONCLUSIONS

A total of 5 dispersion simulations have been performed to assess whether bath treatments at the proposed Tabhaigh East salmon farm will comply with pertinent EQS. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1222 g of azamethiphos for treatment, resulting in a total discharge over 7 days of 9.78 kg and separately 0.176 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 6.

Table 6. Summary of Results

Site Details	
Site Name:	Tabhaigh East
Site Location:	Loch Erisort
Peak Biomass (T):	2,075
Pen Details	
Number of Pens:	8
Pen Circumference (m):	160
Working Depth (m):	15 & 20
Pen Group Configuration:	2 x 4
Azamethiphos Consent	
Recommended 3-hour (g):	1222
Recommended 24-hour (g):	1222
Deltamethrin Consent	
Recommended 6-hour (g)	22

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 1222 g of azamethiphos or 22 g 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 $0.1 \mu\text{g L}^{-1}$, the maximum allowable concentration, and the area where concentrations exceeded the EQS of $0.04 \mu\text{g L}^{-1}$ 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 (Run2) with $K_H=0.05 \text{ m}^2 \text{ s}^{-1}$. 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. Therefore, it is believed that the requested daily quantity of 1222 g of azamethiphos or 22 g of deltamethrin and can be safely discharged at Tabhaigh East without breaching the MAC or EQS.

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