MOWI

Stulaigh South, South Uist

Azamethiphos Dispersion Modelling Report

Mowi Scotland Ltd.

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at a proposed new salmon farm site, Stulaigh South, will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment per day was simulated. Each pen required 750 g of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) for treatment, resulting in a daily release of 750 g and a total discharge over 6 days of 4.5 kg. 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 750 g of azamethiphos, should comfortably comply with the 72-h EQS. The peak concentration during the baseline simulation after 192 hours (72 hours after the final treatment) was less than 0.1 µg/L, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg/L was substantially less than the allowable 0.5 km^2. The baseline simulation presented here was designed to be relatively conservative. Simulations also demonstrated compliance with the 3-h EQS.

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:	Stulaigh South
Site Location:	South Uist
Peak Biomass (T):	3,000
Pen Details	
Number of Pens:	6
Pen Dimensions:	200m circumference
Working Depth (m):	16
Pen Group Configuration:	2 x 3
Azamethiphos	
Recommended 3hr Consent (g):	750
Recommended 24hr Consent (g):	750

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 use topical sealice veterinary medicines on a proposed new marine salmon farm at Stulaigh South, South Uist (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 proposed site biomass and equipment. The modelling procedure follows as far as possible guidance presented by SEPA in January 2022 (SEPA, 2022).

*Figure 1. Location of the proposed Stulaigh South salmon farm (top) and the location of the ADCP deployments ID208 and ID224 (▲) relative to the proposed pen positions (**o**).*

1.1 Site Details

The proposed site is situated south of Stulaigh Island, South Uist (Figure 1). Details of the site are provided in Table 2. The receiving water is defined as open water.

Table 2. Project Information

Site Details		
Site Name:	Stulaigh South	
Site Location:	South Uist	
Peak Biomass (T):	3,000	
Proposed Feed Load (T/yr)	7,665	
Proposed Treatment Use:	Azamethiphos	
Pen Details		
Group Location:	NF833221	
Number of Pens:	6	
Pen Dimensions:	200m circumference	
Grid Matrix (m):	120	
Working Depth (m):	16	
Cone depth (m):	15	
Pen Group Configuration:	2 x 3	
Pen Group Orientation (°G):	165	
Pen Group Distance to Shore (km):	0.39	
Water Depth at Site (m):	43	
Hydrographic Data		
	ID208	**ID224**
Current Meter Position:	83371, 822233	83559, 822178
Depth at Deployment Position (m):	43	40
Surface Bin Centre Height Above Bed (m):	36.71	35.72
Middle Bin Centre Height Above Seabed (m):	29.71	25.72
Bottom Bin Centre Height Above Bed (m):	3.71	3.72
Duration of Record (days):	39	83
Start of Record:	08/03/2018	22/05/2018
End of Record:	17/04/2018	14/08/2018
Current Meter Averaging Interval (min):	20	20
Magnetic Correction to Grid North:	-4.17	-4.13
Bath Treatments		
3hr Recommended Consent Mass (g):	750	
24hr Recommended Consent Mass (g):	750	

2 MODEL DETAILS

2.1 Model Selection

The hydrodynamic model used in the Stulaigh South Azamethiphos Dispersion Modelling (Mowi Scotland Ltd., 2022) and solids marine modelling was FVCOM. 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.

2.2 Model Domain and Boundary Conditions

The unstructured mesh to be used in the marine modelling is shown in Figure 2. The model resolution was enhanced in the area around the Mowi site at Stulaigh South (Figure 3). The spatial resolution of the model varied from 25m in some inshore waters and round the farm pens to 500 m along the open boundary. The model consisted of 7,310 nodes and 13,699 triangular elements. Model bathymetry was taken from the European Marine Observation and Data Network (EMODnet, https://www.emodnet-bathymetry.eu/), supplemented by a multibeam survey undertaken in June 2021 (Mowi, 2022). The combined data were interpolated onto the South Uist model mesh (Figure 4).

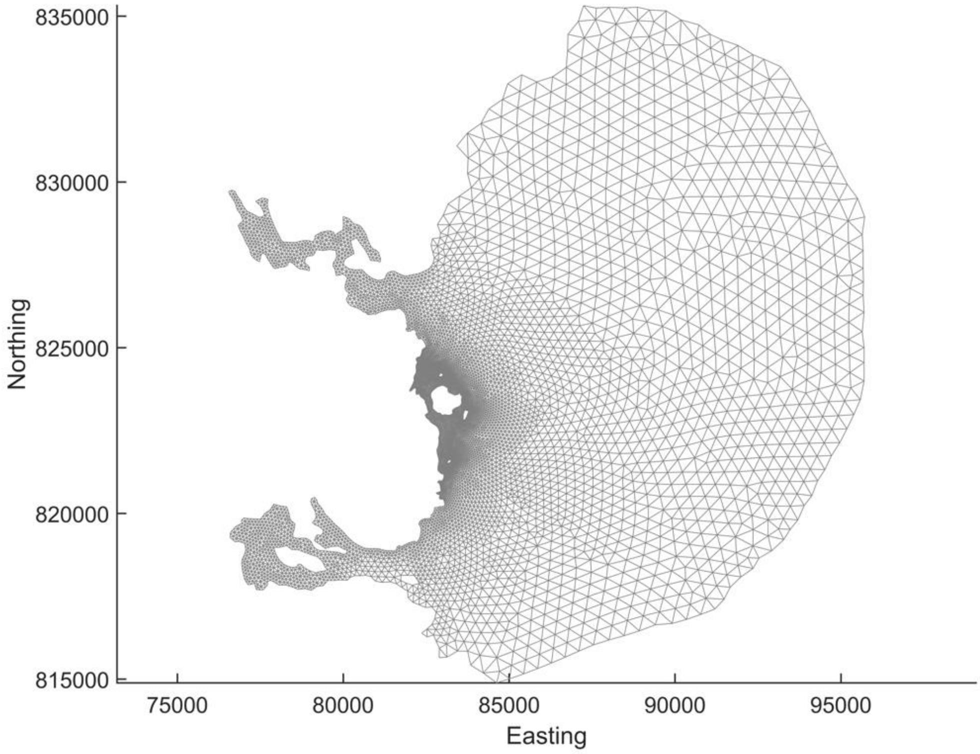

Figure 2. The mesh and domain of the modelling study, adapted from the ECLH sub-model.

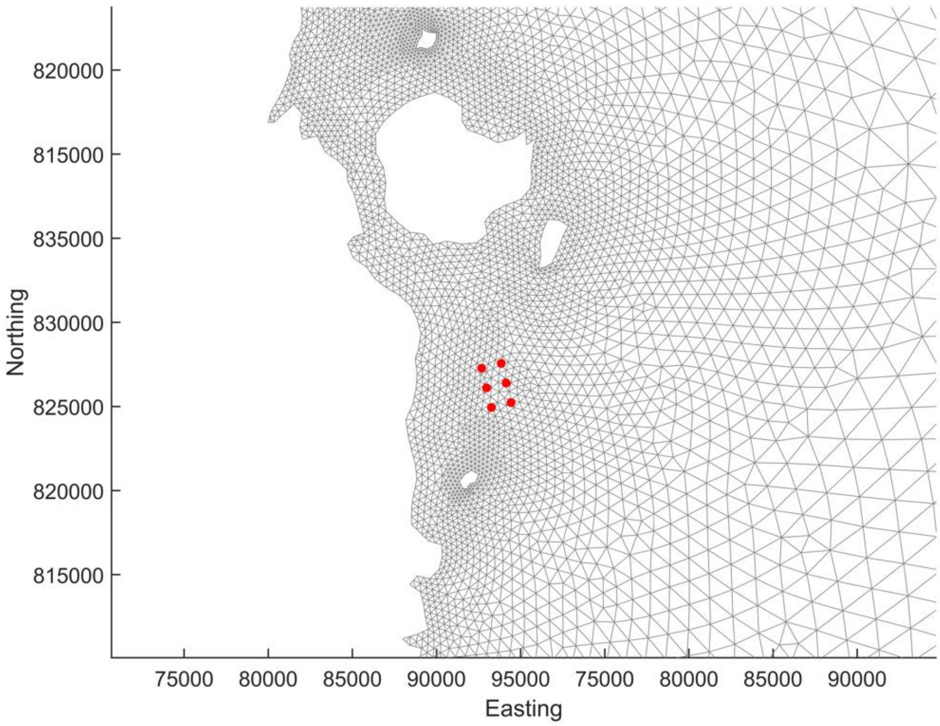

Figure 3. The unstructured mesh around the proposed Stulaigh South site in the modified model grid, with the proposed pen locations indicated (o).

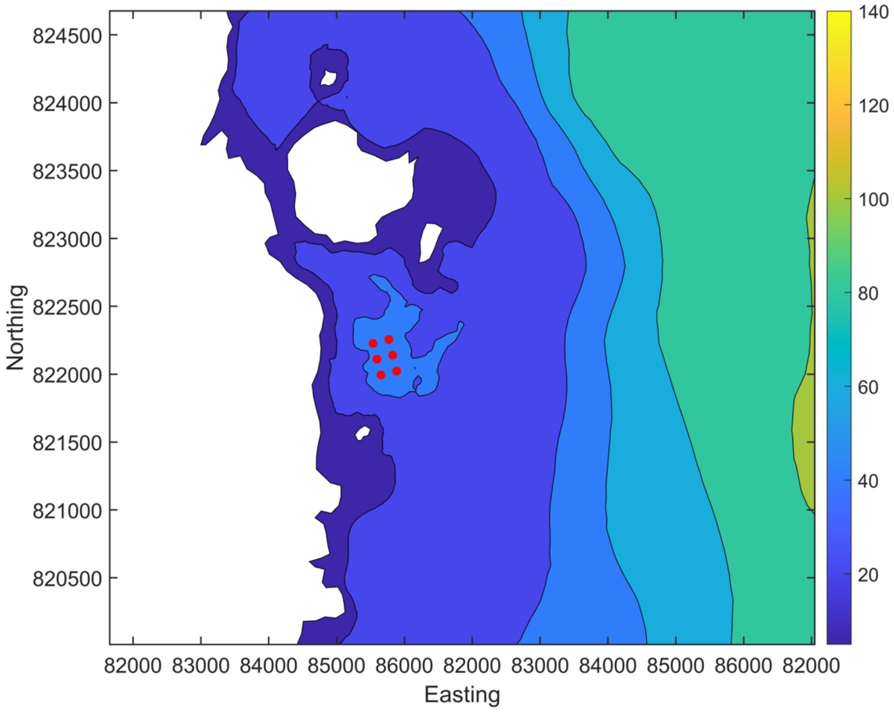

Figure 4. Localised bathymetry (m) around Stulaigh South from the modified model.

The model was forced along its open boundary 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 RiCOM hydrodynamic model (Walters et al., 2010; Gillibrand et al., 2016b) on the ECLH grid, which was, in turn, forced by eight tidal constituents (M_2, S_2, N_2, K_2, O_1, K_1, P_1 and Q_1) taken from the full Scottish Shelf Model (SSM). Wind speed and direction data were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis product (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), with data interpolated onto the nodal locations of the model mesh.

Full details of the calibration and validation of the hydrodynamic model are given in the Marine Modelling report (Mowi, 2022).

2.3 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the UnPTRACK model (Gillibrand, 2021), 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 9 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 2.36 m was chosen as a realistic net depth during application of the medicine for 200m 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 4.5 kg of azamethiphos released during treatment of the whole farm (6 pens). Particles were released from random positions within a pen radius of the centre and within the 0 – 2.36 m depth range. The simulations used *ca. 450696* numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation ran for a total of 217 hours (9.04 days). This covered the treatment period (96 hours), a dispersion period to the EQS assessment after 192 hours (72 hours after the final treatment), and an extra 25 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 60m x 60m squares (comparable to the pen diameter) using the same depth range as the treatment depth (i.e. 0 – 2.36 m). Using a regular grid for counting makes calculating particle concentrations and presenting the results easier.

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

(i) The maximum concentration (µg/L) 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 2018 (ID208) (Figure 5). A further set of simulations was performed over neap tides in 2018 (ID224) to confirm the adequacy of dispersion during the weakest tides (Figure 6).

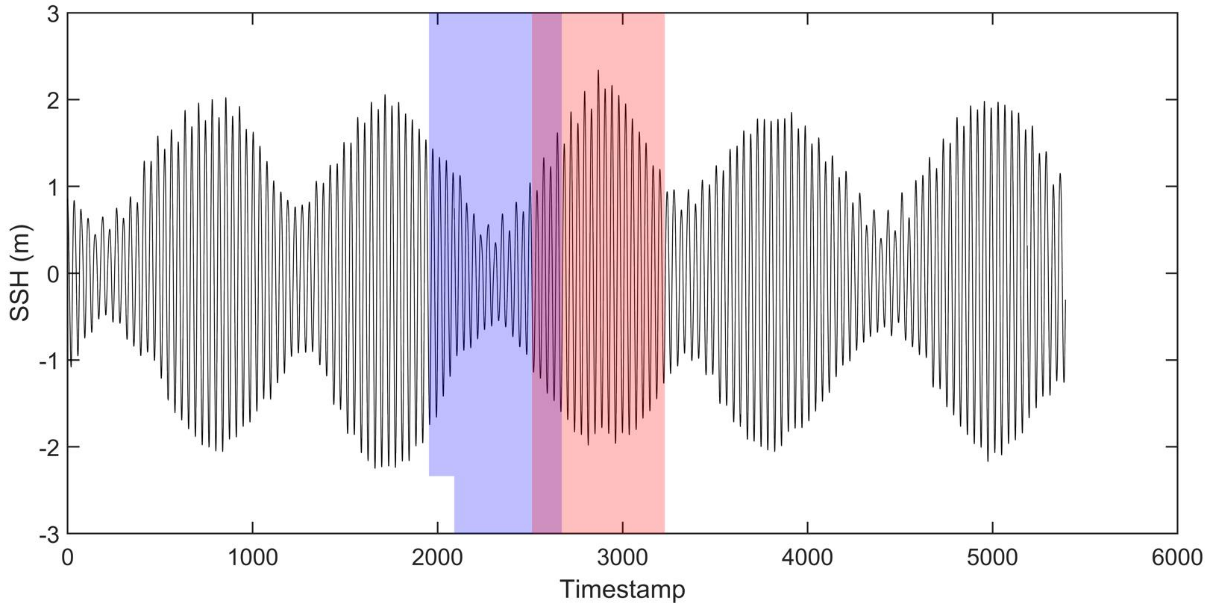

Figure 5. Sea surface height (SSH) at Stulaigh South from 8th March –17th April 2018 (ID208). Dispersion simulations were performed over periods of neap tides (blue, start day 5th April 2018) and spring tides (red, start day 13th April 2018)

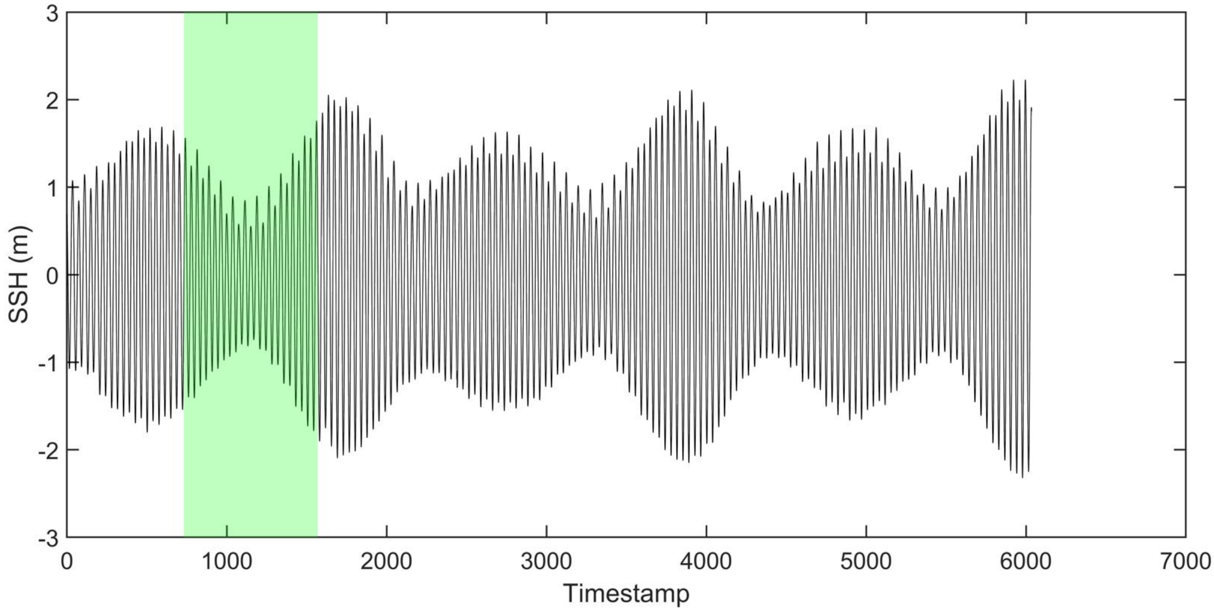

Figure 6. Sea surface height (SSH) at Stulaigh South from 22nd May 2018 – 14th August 2018 (ID224). Dispersion simulations were performed over periods of neap tides (green, start day 3rd June 2018).

2.4 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 5 and Figure 6.

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 5 and Figure 6.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (kg)	Release Time (hr)
1	83268	822227	2.36	0.75	0
2	83385	822256	2.36	0.75	24
3	83298	822111	2.36	0.75	48
4	83414	822140	2.36	0.75	72
5	83327	821994	2.36	0.75	96
6	83444	822024	2.36	0.75	120

Table 4. Dispersion model simulation details for the treatment simulations of 6 pens at Stulaigh South.

Set	Run No.	T 1/2 (h)	Kh	Kv	Start Time
Neap Tides, Start day = 28 (5th April 2018, ID208)					
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	213.6	0.1	0.001	00:00
	9	55.2	0.1	0.001	00:00
3	10	134.4	0.18	0.001	00:00
	11	134.4	0.05	0.001	00:00
4	12	134.4	0.1	0.0025	00:00
	13	134.4	0.1	0.005	00:00
Spring Tides, Start day = 35 (13th April 2018, ID208)					
5	14	134.4	0.1	0.001	00:00
	15	213.6	0.1	0.001	00:00
	16	55.2	0.1	0.001	00:00
6	17	134.4	0.18	0.001	00:00
	18	134.4	0.05	0.001	00:00
7	19	134.4	0.1	0.0025	00:00
	20	134.4	0.1	0.005	00:00
Neap Tides, Start day = 12 (3rd June 2018, ID224)					
8	21	134.4	0.1	0.001	00:00
	22	213.6	0.1	0.001	00:00
	23	55.2	0.1	0.001	00:00
9	24	134.4	0.18	0.001	00:00
	25	134.4	0.05	0.001	00:00
10	26	134.4	0.1	0.0025	00:00
	27	134.4	0.1	0.005	00:00

2.5 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, 2022). 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 0.095 m s^{-1} was used from ID208 (Table 5), this deployment was chosen as it had the slowest surface speed of the two deployments, for a conservative approach, and was deployed closer to the proposed pens, and hence more representative of the site.

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})	0.095
Area of 200m pen (m^2)	3,183
Distance from shore (km)	0.49
Mean water depth (m)	46.54
Treatment Depth (m)	2.36
Mixing zone ellipse area (km^2)	**0.149804**

For the 3-hour EQS assessment, the baseline runs for neap and spring tides (Runs 1 and 14 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 10m x 10m grid (rather than a 60m x 60m grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

2.6 Diffusion Coefficients

Selection of the horizontal diffusion parameter, K_H, was guided by dye releases conducted at the near-by Stulaigh site by Anderson Marine Surveys Ltd on 25th April 2017, 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 Stulaigh gave a mean horizontal diffusivity of 0.18 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.

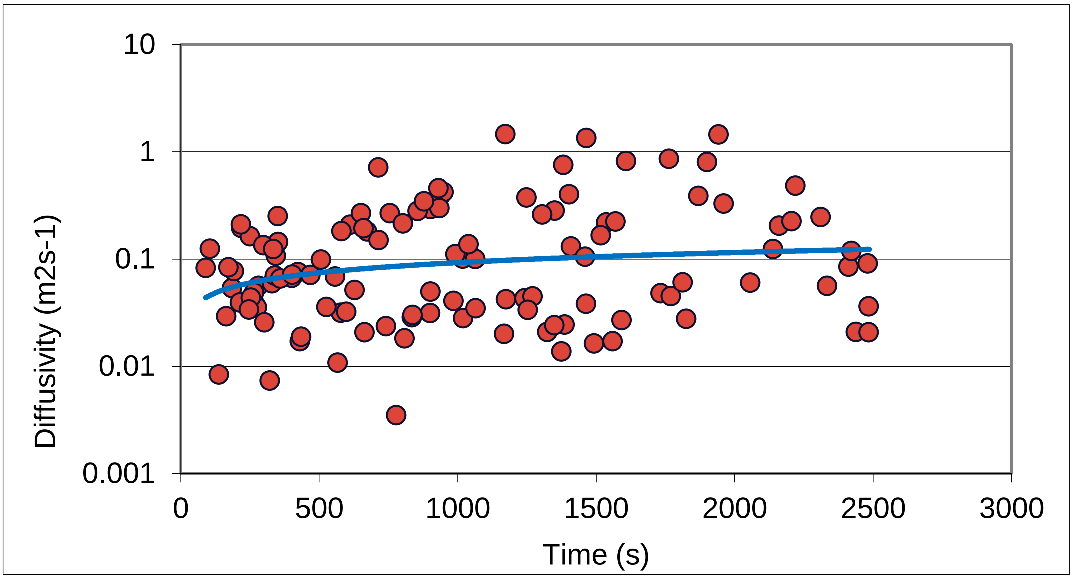

Figure 7. Estimated horizontal diffusivity (m^2 s^{-1}) from dye release experiments at Stulaigh on 25th April 2017. The mean diffusivity was 0.18 m^2 s^{-1}.

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:

$$C_{max} = \frac{M}{4\pi HKt} \quad (1)$$

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 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 to be made.

A number of dye releases have been conducted for Mowi Scotland Ltd in recent years to assess horizontal diffusivity at salmon farm sites. The maximum concentration measured in each post-release survey was identified (each comprised of a number of individual transects) and was then plotted against the nominal time for that survey (typically accurate to ±15 minutes). The results are shown in Figure 8. A nominal mixed depth of H = 5m was used (see also Dale et al., 2020).

The results support the notion that horizontal diffusivity in the Scottish marine environment is typically greater than 0.1 m^2 s^{-1}. The observed maximum concentrations, particularly after about 15 minutes (900s), fall faster than a diffusivity of 0.1 m^2 s^{-1} would imply, indicating greater diffusion. There is considerable uncertainty in the data, because it is difficult during dye surveys to repeatedly measure the point of peak concentration. Nevertheless, we can say that no data thus far collected infer a horizontal diffusion coefficient of less than 0.1 m^2 s^{-1}. At periods longer than one hour (3600s), none of the data implied a horizontal diffusivity of less than 0.3 m^2 s^{-1}. We can conclude that using K_H = 0.1 m^2 s^{-1} is a conservative value for modelling bath treatments over periods greater than about half-an-hour.

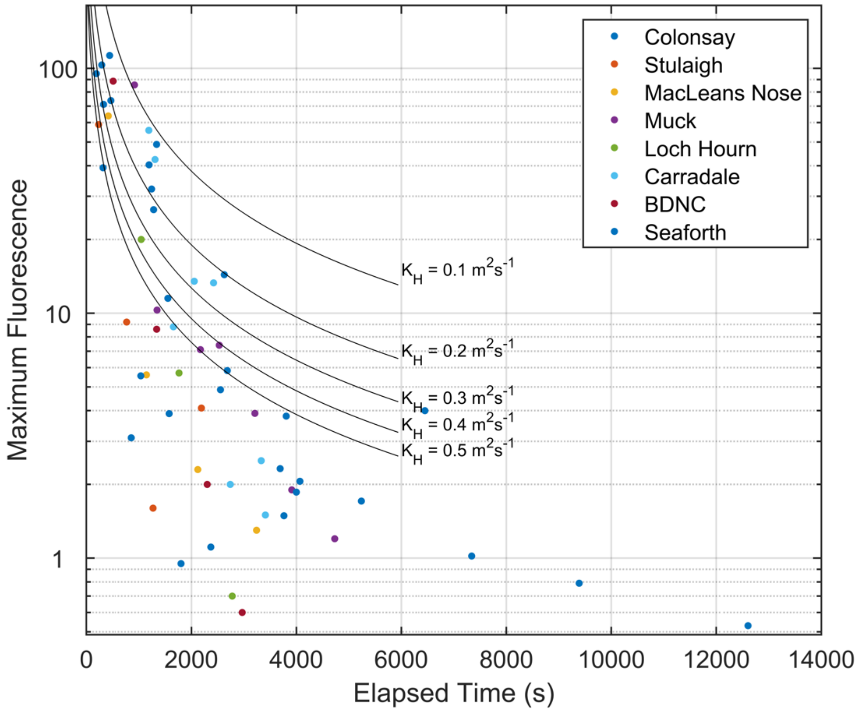

Figure 8. Maximum fluorescence measured following dye releases at a number of Mowi sites in Scotland. The black lines indicate the rate at which the maximum concentration would fall at different horizontal diffusivities.

A similar conclusion was reached by Dale et al (2020) following dye releases conducted in Loch Linnhe and adjacent waters.

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.

3 RESULTS

3.1 Dispersion During Neap Tides, April 2018 (ID208)

A standard treatment of 6 x 200m pens, with a reduced net depth of 2.36 m and assuming 1 pen could be treated per day at a treatment concentration of 100 µg/L, resulted in a treatment mass per pen of azamethiphos of 750 g, a daily (24-h) release of the same mass of 750 g and a total treatment release of 4.5 kg over 120 hours. The dispersion of the medicine during and following treatment from Run001 (Table 4) is illustrated in Figure 9. After 24 hours, as the 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, 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). The maximum concentration at this time was again about 100 µg/L, due to the release of the fourth treatment.

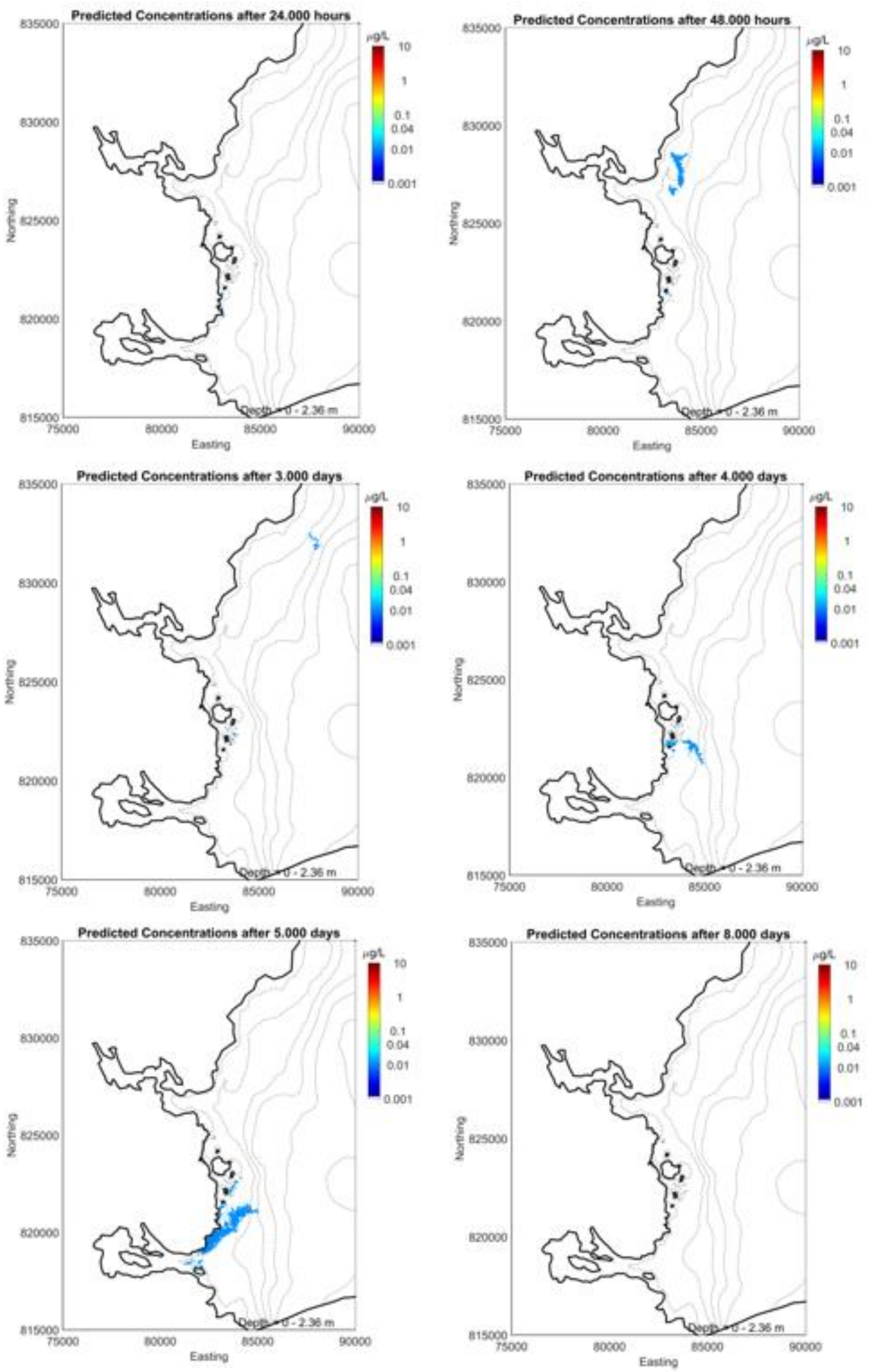

Figure 9. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 48 hours (top right), 72 hours (middle left), 96 hours (middle right), 120 hours (bottom left) and 192 hours (bottom right).

The treatment schedule completed after 120 hours (5 days). At this stage, the medicine released on earlier days had already dispersed. 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 final treatment at 120 hours, the treatment patches were rapidly dispersed and concentrations rapidly fell away below the EQS.

The time series of maximum concentration from this simulation is shown in Figure 10. The 6 peaks in concentration of ~100 µg/L following each treatment event over the first 5 days are evident. Following the final treatment after 120 hours, the maximum concentration fell steadily away (Figure 10). A default half-life of 134.4 h (5.6 days) was used for the baseline run. The maximum concentration seventy-two hours after the final treatment (time = 192 hours) was well below 0.1 µg/L, the maximum allowable concentration (MAC).

The area where the EQS of 0.04 µg/L was exceeded peaked at about 0.8 km^2 following the fifth treatment, but had fallen below 0.5 km^2 within 48h of the final treatment; by 72h after the final treatment, the exceeded area was close to zero (Figure 9 and 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 environmental quality standards are comfortably achieved. The sensitivity of the model results to the medicine half-life, diffusion coefficients and tidal state were examined and these run results are included in Figure 10, Figure 11 & Figure 12.

3.2 Sensitivity to Half-Life

The EQS was achieved, and was comfortably passed with all half-lives used (Figure 10). The area where the EQS of 0.04 µg/L is exceeded peaked at about 0.8 km^2 following the fifth treatment, but had fallen well below 0.5 km^2, for all simulated half-lives, within 72 hours of the final treatment (Figure 10). The area remained below 0.5 km^2 thereafter.

3.3 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 baseline 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 = 0.18 $m^2 s^{-1}$ and K_H = 0.05 $m^2 s^{-1}$ (Table 4). The time series confirm that the MAC was not exceeded after 192 hours (72 hours after the final treatment) with any of the different horizontal diffusion coefficients. 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. 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.

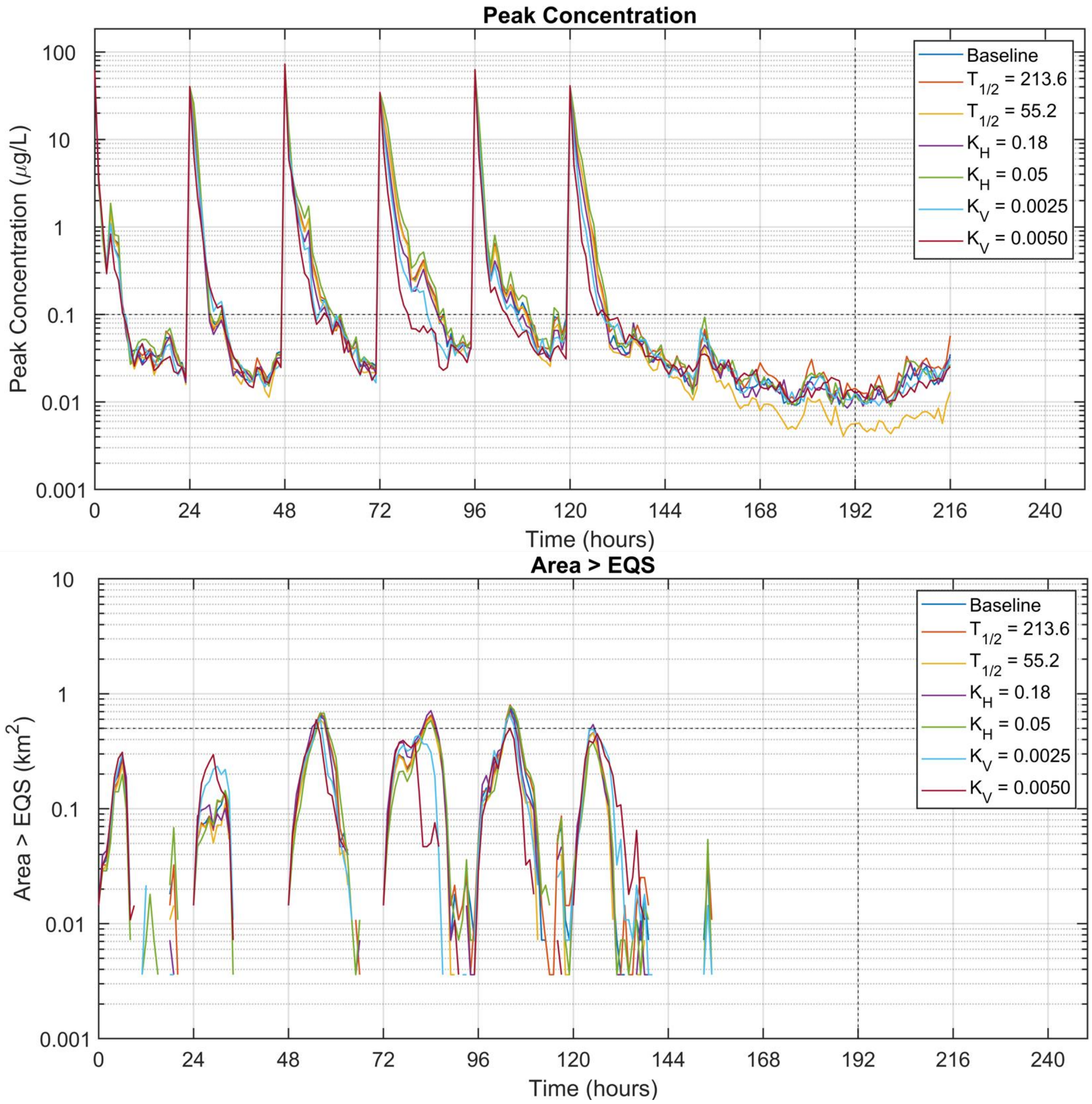

Figure 10. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the baseline and second, third and fourth sets of model runs (Table 4). The model was run during neap tide with varying medicine half-life $T_{1/2}$ (hours), horizontal diffusion coefficient K_H ($m^2 s^{-1}$) and vertical diffusion coefficient K_V ($m^2 s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.4 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.

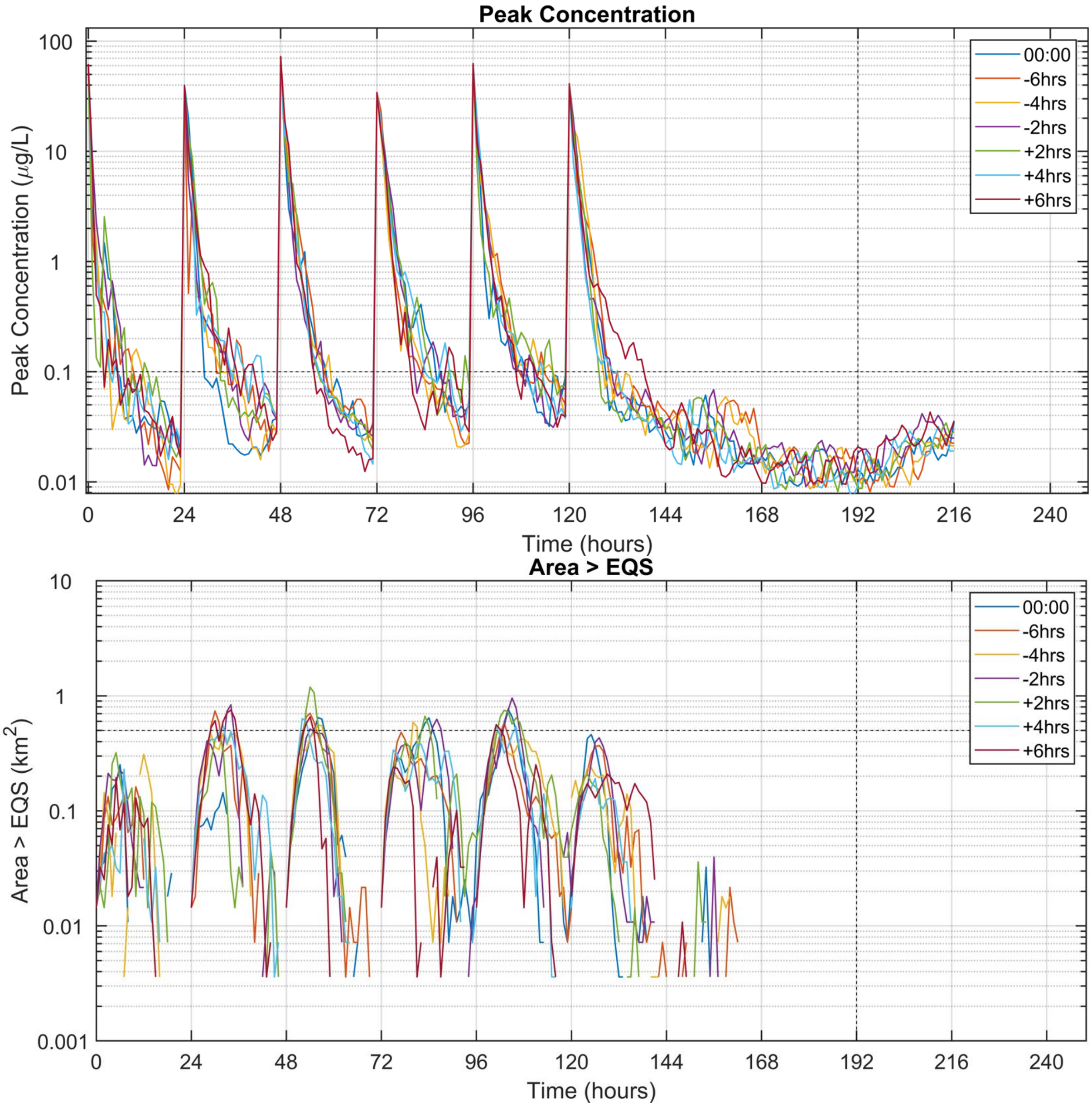

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.5 Dispersion during Spring Tides, April 2018 (ID208)

Dispersion simulations were carried out during modelled spring tides in April 2018 (Figure 5), 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 750 g of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were achieved (Figure 12).

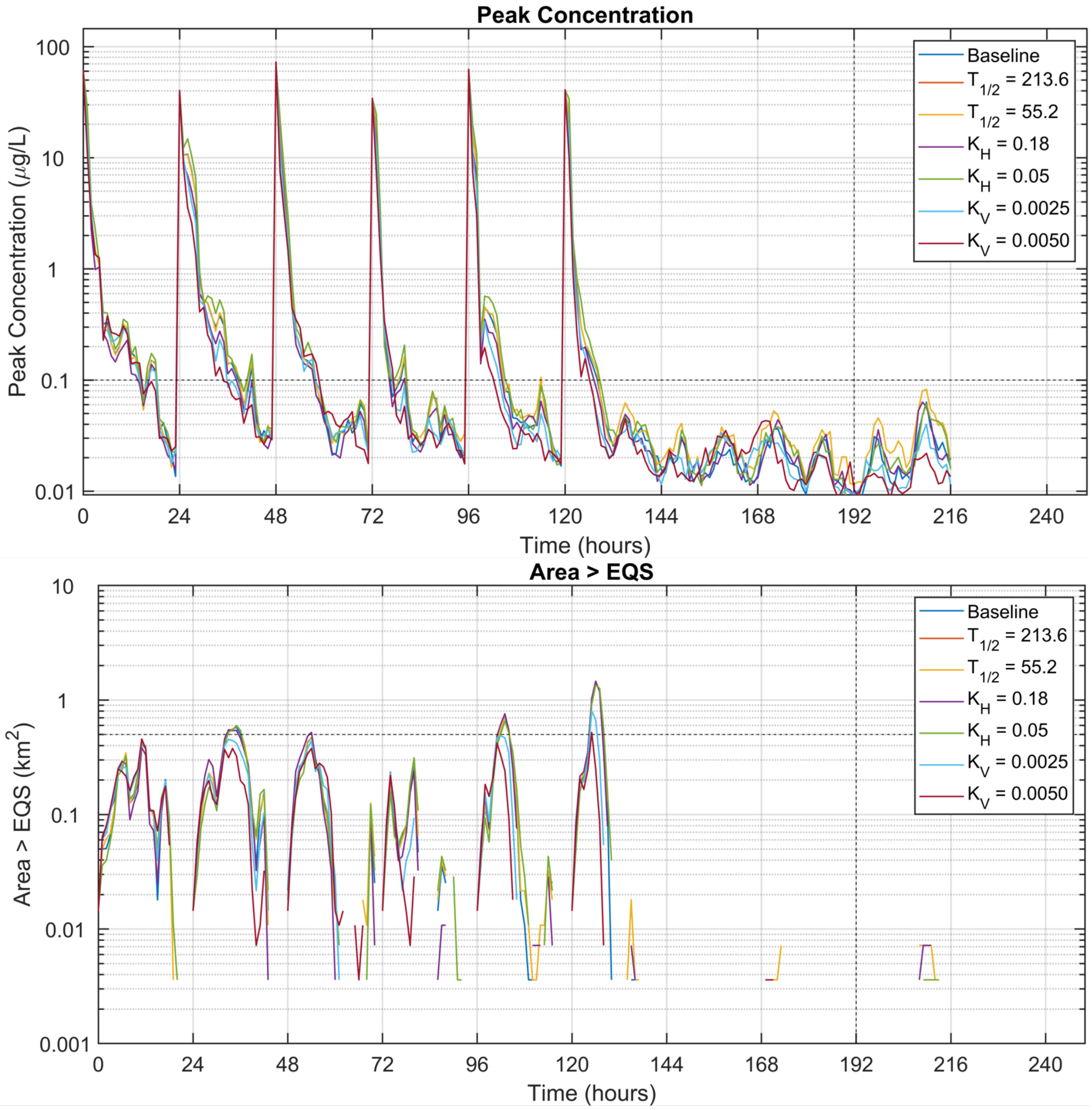

Figure 12. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life $T_{1/2}$ (hours), horizontal diffusion coefficient K_H (m^2 s^{-1}) and vertical diffusion coefficient K_V (m^2 s^{-1}). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.6 Dispersion During Neap Tides, June 2018 (ID224)

A further set of dispersion simulations during modelled neap tides in June 2018 were carried out (Figure 6), repeating the main set carried out for neap tides in April 2018 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 750 g of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved (Figure 13). These simulations demonstrate again that the modelled treatment regime will comfortably meet the EQS criteria.

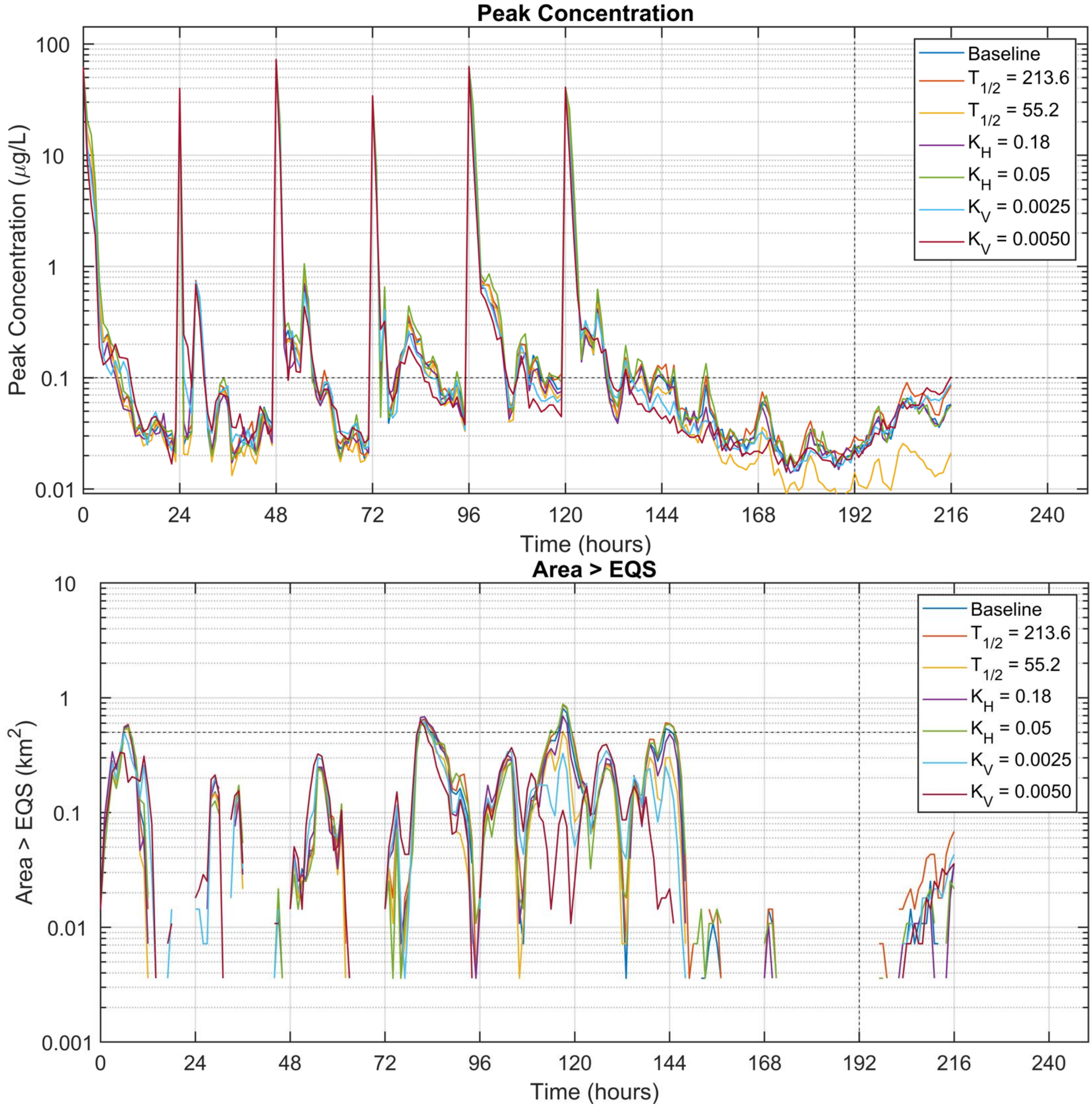

Figure 13. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, nineth and tenth set of model runs (Table 4). The model was run at neap tides from July 2018 with varying medicine half-life $T_{1/2}$ (hours), horizontal diffusion coefficient 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 = 192 h) of 0.1 g/L and 0.5 km² are indicated by the horizontal dashed lines.

3.7 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 9.5 cm s^{-1} was used from ID208 (Table 1) which was thought to be a representative value for the surface 0-2.36m layer at Stulaigh South. 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 5th April 2018) are shown in Figure 14. For each treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.149 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 13th April 2018), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 15). 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 750 g of azamethiphos from each of the six proposed 200m pens at Stulaigh South should not breach the 3-hour Environmental Quality Standard.

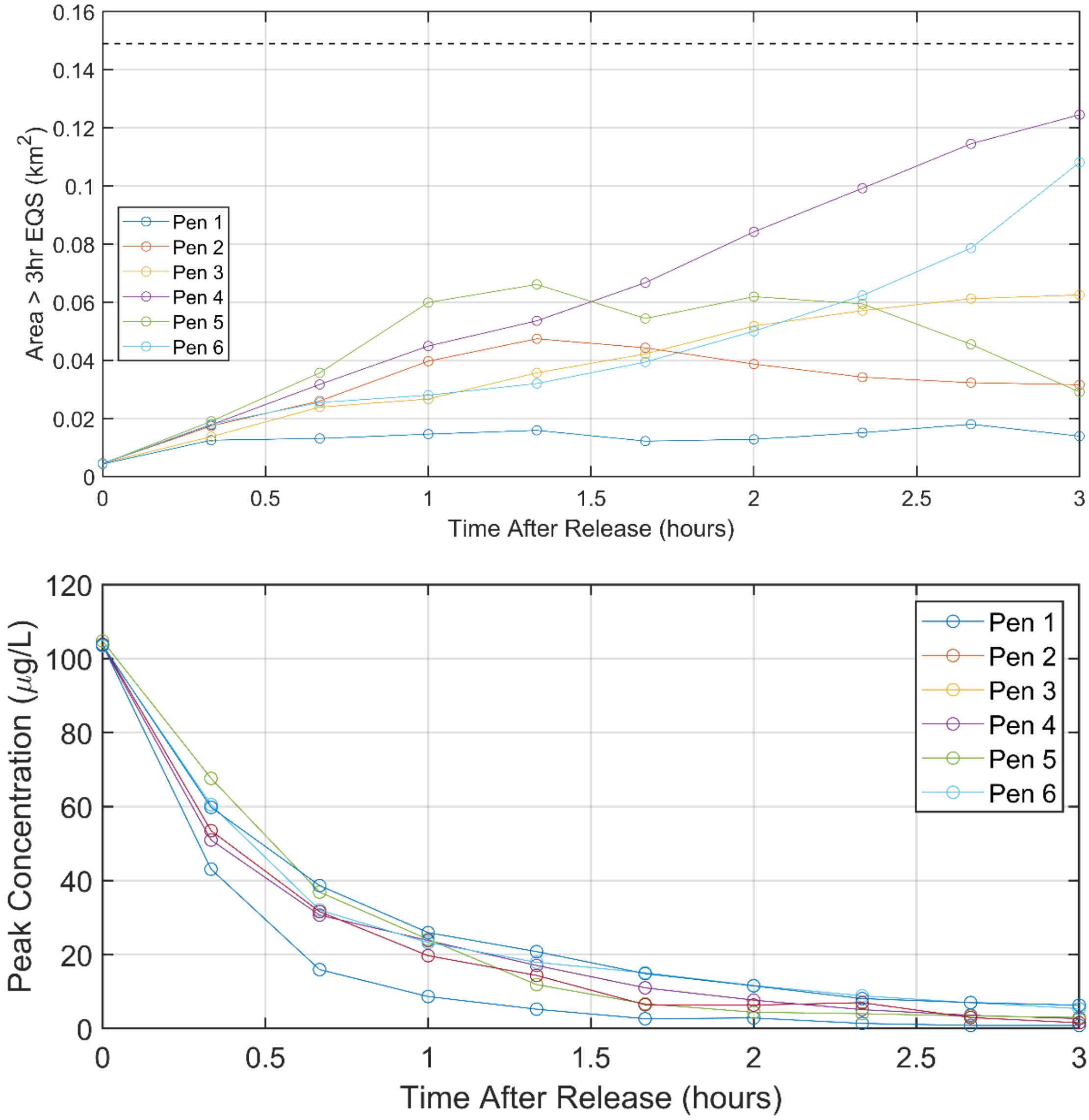

Figure 14. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

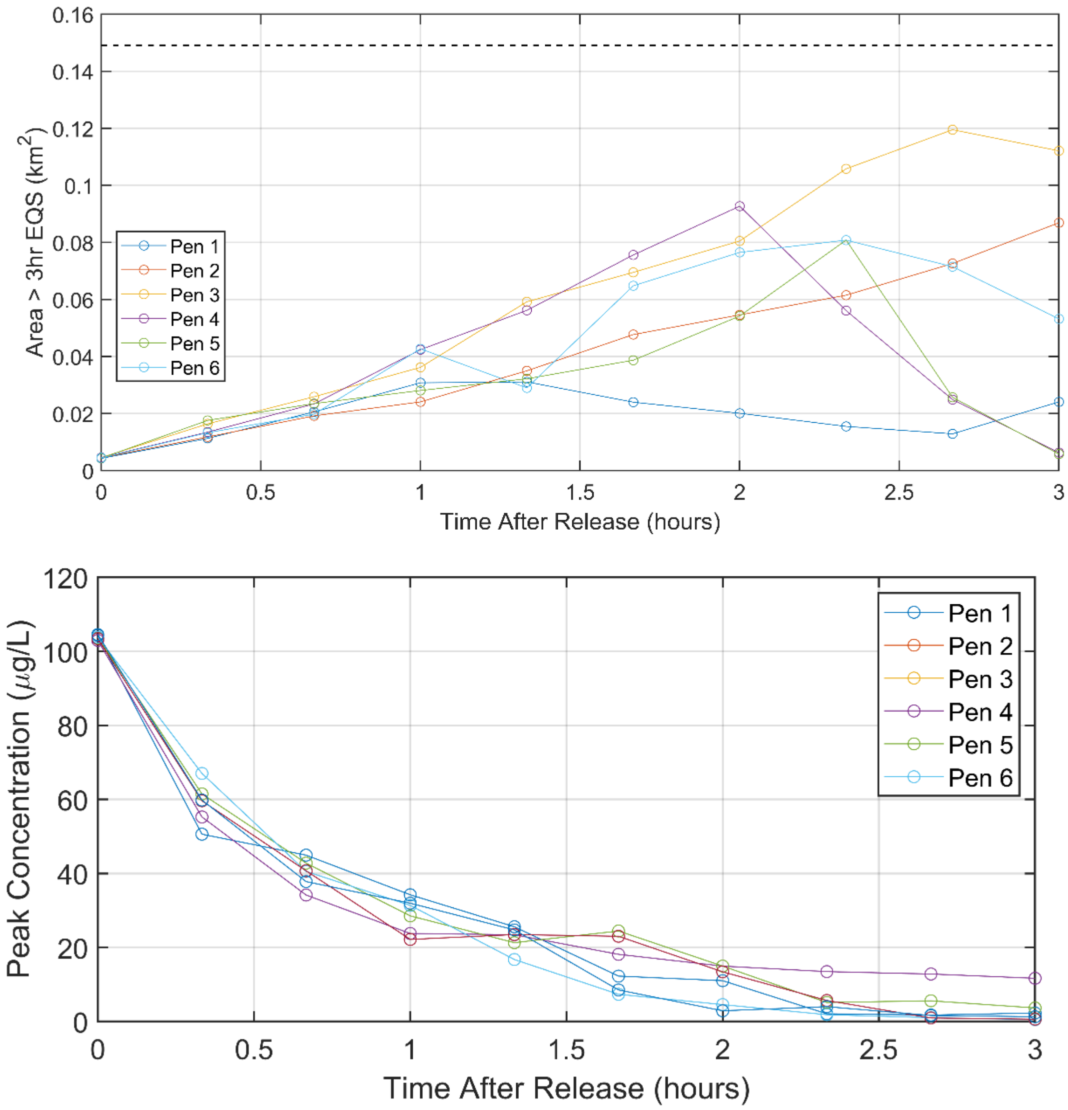

Figure 15. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area indicated (---).

4 SUMMARY AND CONCLUSIONS

A total of 29 dispersion simulations have been performed to assess whether bath treatments at the proposed Stulaigh South salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 750 g of azamethiphos for treatment, resulting in a total discharge over 6 days of 4.5 kg. 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:	Stulaigh South
Site Location:	South Uist
Peak Biomass (T):	3,000
Pen Details	
Number of Pens:	6
Pen Dimensions:	200m circumference
Working Depth (m):	16
Pen Group Configuration:	2 x 3
Azamethiphos	
Recommended 3hr Consent (g):	750
Recommended 24hr Consent (g):	750

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 750 g, should consistently comply with the 72-h EQS. The peak concentration during the baseline simulation after 192 hours (72 hours after the final treatment) was less than 0.1 µg/L, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg/L was substantially less than the allowable 0.5 km^2. In all simulations performed, including sensitivity testing, the EQS and MAC criteria were met. Further simulations over a neap tide from 2018 demonstrated that the modelled treatment regime consistently complied with the relevant EQS and MAC. For the simulation 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 750 g of azamethiphos can be safely discharged at Stulaigh South without breaching the MAC or EQS. Simulations also demonstrated compliance with the 3-h EQS.

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 times scales greater than a few hours (e.g. Okubo, 1971; Edwards, 2015), as illustrated in Figure 9.

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