Azamethiphos Dispersion Modelling
Isle of Muck, CAR/L/1109999

Mowi Scotland Limited

March 2022

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Muck salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1.02 kg of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) for treatment, resulting in a daily release of the same amount due to one pen being treated per day and a total discharge over 8 days of 8.16 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 1.02 kg of azamethiphos, should comfortably comply with the EQS. The peak concentration during the baseline simulation after 240 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.

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:	Muck
Site Location:	Isle of Muck
Peak Biomass (T):	4,069
Pen Details	
Number of Pens:	8
Pen Dimensions:	160m circumference
Working Depth (m):	15
Pen Group Configuration:	2 x 4
Azamethiphos	
Recommended 3hr Consent (kg):	1.02
Recommended 24hr Consent (kg):	1.02

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 marine salmon farm at the Isle of Muck (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).

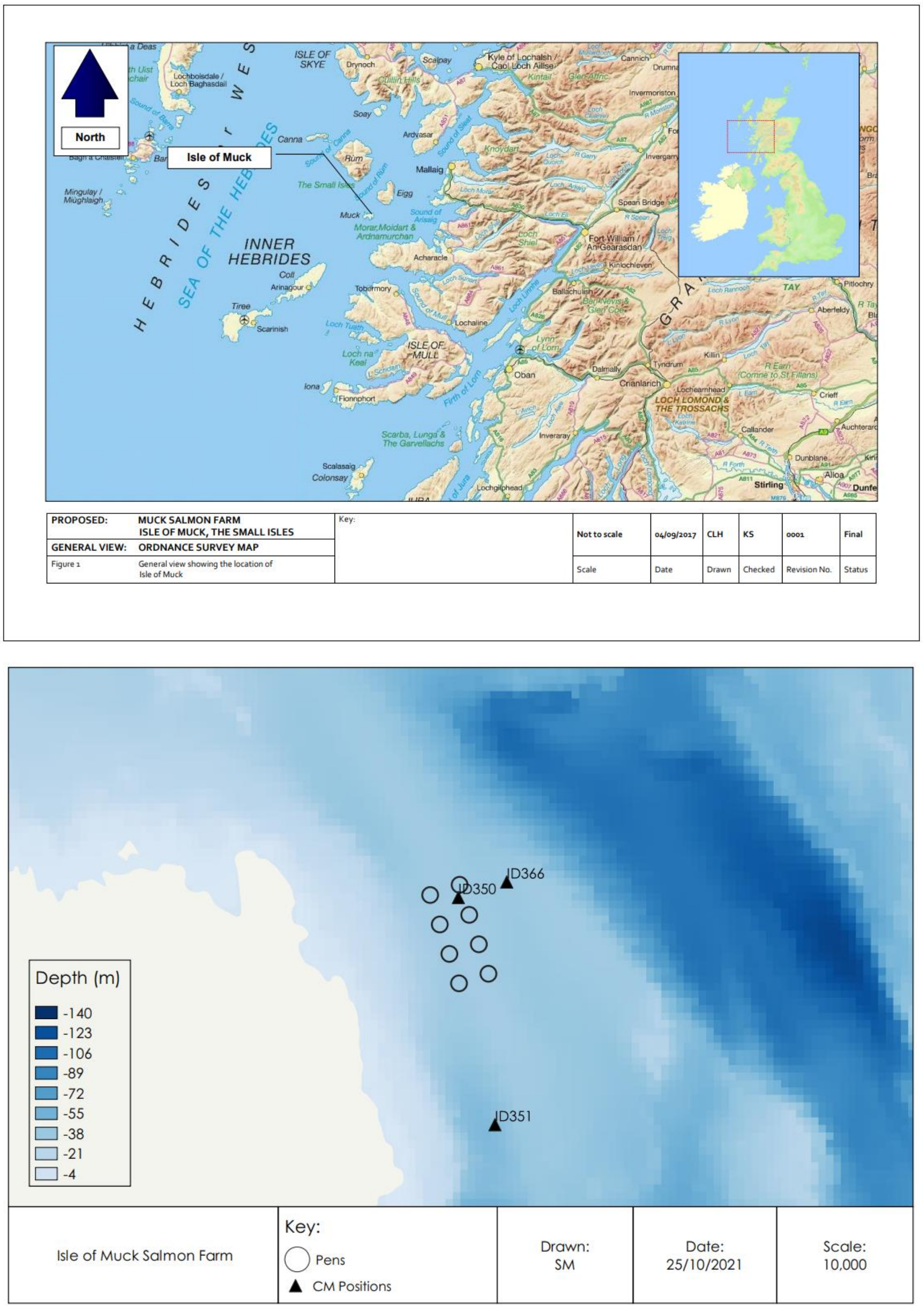

*Figure 1. Location of Muck salmon farm (top) and the location of the ADCP deployments (▲) relative to the proposed pen positions (**o**).*

1.1 Site Details

The site is situated off the East of the Isle of Muck (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:	Muck		
Site Location:	Isle of Muck		
Peak Biomass (T):	4,069		
Proposed Feed Load (T/yr)	10,396		
Proposed Treatment Use:	Azamethiphos		
Pen Details			
Group Location:	NM 43201 80365		
Number of Pens:	8		
Pen Dimensions:	160m circumference		
Grid Matrix (m):	100		
Working Depth (m):	15		
Cone depth (m):	15		
Pen Group Configuration:	2 x 4		
Pen Group Orientation (°G):	-18		
Pen Group Distance to Shore (km):	0.4		
Water Depth at Site (m):	35		
Hydrographic Data			
	ID350	**ID351**	**ID366**
Current Meter Position:	143198, 780484	143316, 779751	143354, 780534
Depth at Deployment Position (m):	35.6	48.8	39.61
Surface Bin Centre Height Above Bed (m):	28.42	40.92	30.71
Middle Bin Centre Height Above Seabed (m):	17.42	30.42	22.71
Bottom Bin Centre Height Above Bed (m):	3.42	3.42	3.71
Duration of Record (days):	40	40	77
Start of Record:	08/04/2010	08/04/2010	27/01/2021
End of Record:	19/05/2010	19/05/2010	15/04/2021
Current Meter Averaging Interval (min):	20	20	20
Magnetic Correction to Grid North:	-5.08	-5.07	-3.12
Bath Treatments			
3hr Recommended Consent Mass (kg):	1.02		
24hr Recommended Consent Mass (kg):	1.02		

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 Environmental Quality Standards. The modelling approach is described in full in the Hydrodynamic Model Description (Mowi Scotland Ltd, Muck Hydrodynamic Model Description, February 2022), 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, 2021) 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 Environmental Quality Standards (EQS) e.g. 72 hours after the final treatment. Here, we have modelled the dispersion of azamethiphos following a treatment scenario at Muck to illustrate the quantities of medicine that disperse safely in the environment.

2.2 Model Domain and Boundary Conditions

The unstructured mesh used in the modelling was adapted from the mesh used by Gillibrand et al (2016b) (Figure 2). This domain was chosen so that the open boundary would be further away from the site of interest than is the case with the Marine Scotland ECLH and WLLS domains. Model resolution was enhanced in the Small Isles region, particularly around the Mowi site at Muck (Figure 3). The spatial resolution of the model varied from 25m in some inshore waters to 20km along the open boundary. The model consisted of 119,925 nodes and 231,016 triangular elements. Bathymetry was taken from the European Marine Observation and Data Network (EMODnet), shown in Figure 4.

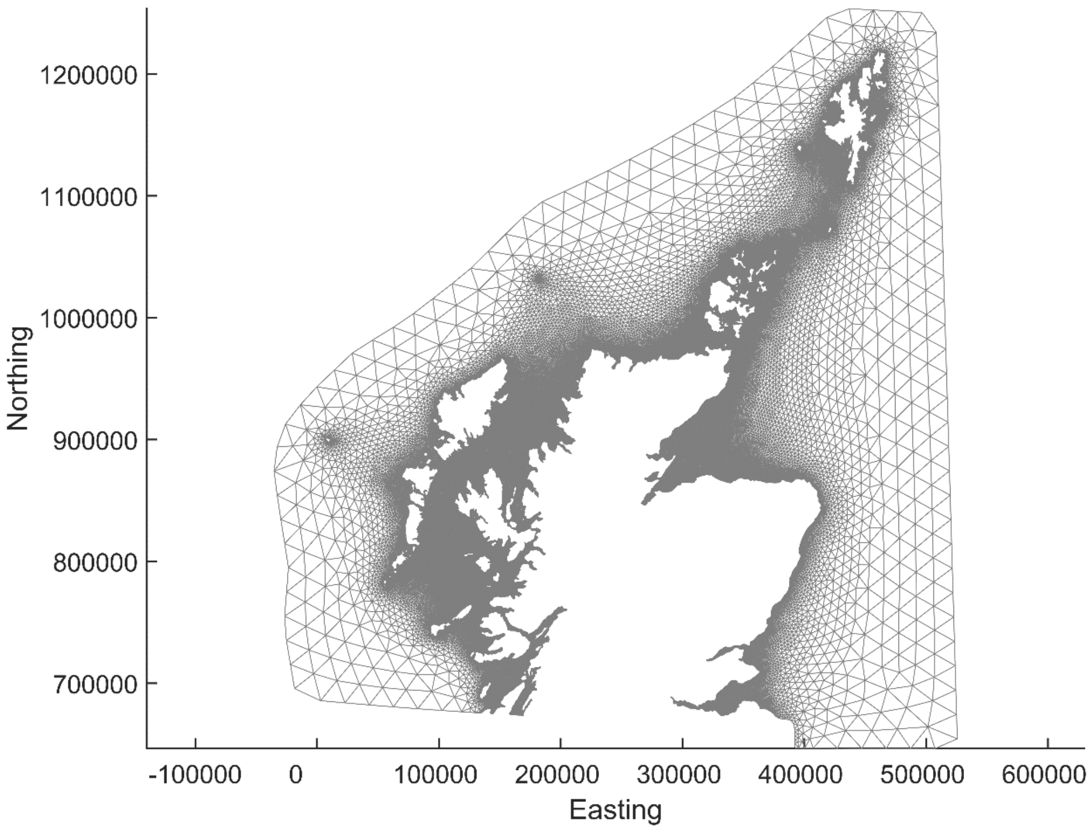

Figure 2. The mesh and domain of the modelling study, adapted from Gillibrand et al (2016b).

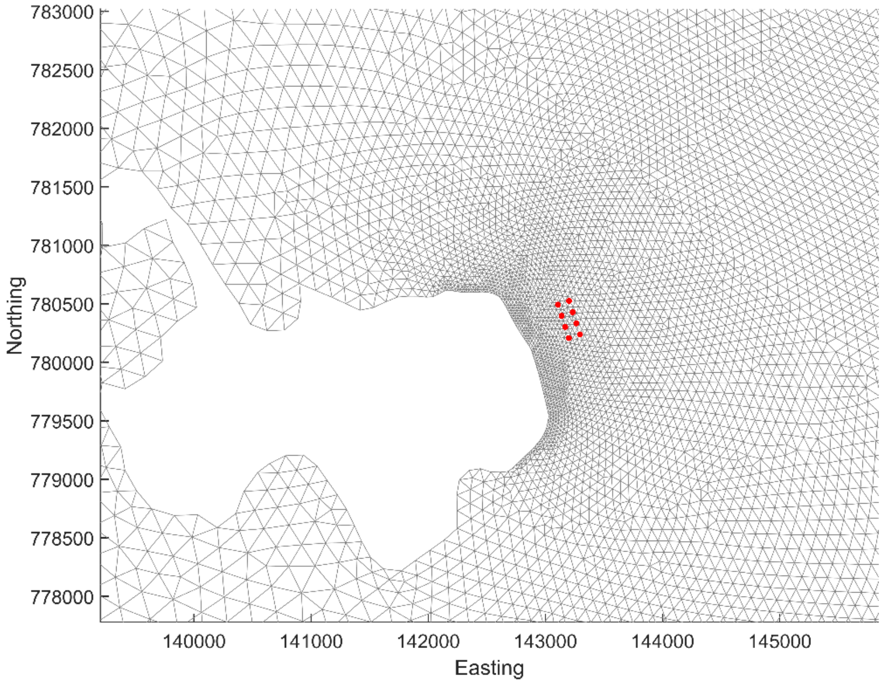

Figure 3. The unstructured mesh around the Muck site in the modified model grid, with the proposed pen locations indicated (o).

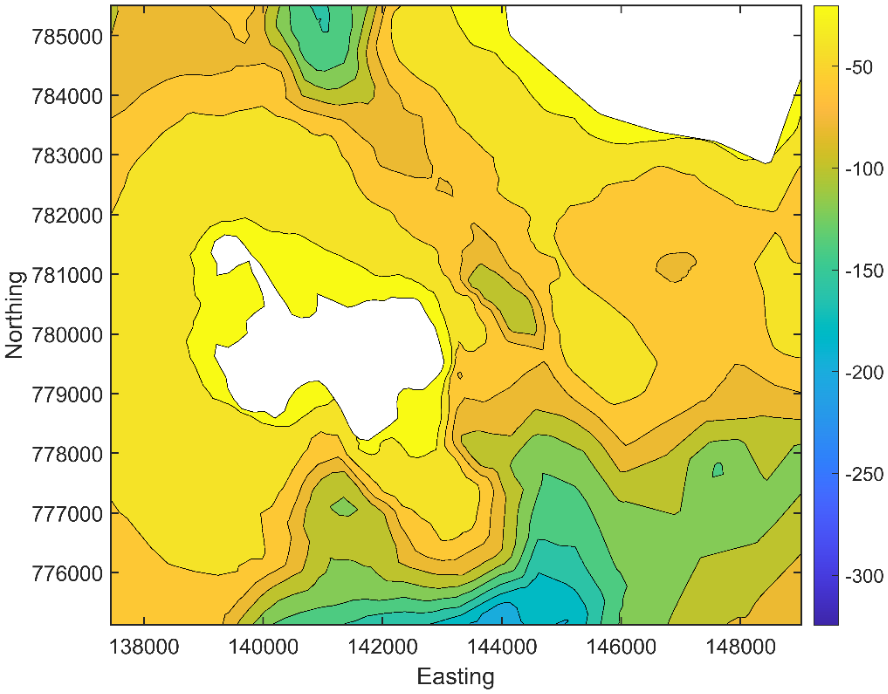

Figure 4. Localised bathymetry (m) around Muck from the modified model.

The model was forced at the outer boundaries by eight tidal constituents (O_1, K_1, P_1, Q_1, M_2, S_2, N_2, K_2) which were taken from the Scottish Shelf Model (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 Hydrodynamic Model Description (Mowi Scotland Ltd, Muck Hydrodynamic Model Description, 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 eleven 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 160m pens. The initial mass released per pen was calculated from the reduced pen volume and a treatment concentration of 100 µg/L, with a total mass of 8.16 kg of azamethiphos released during treatment of the whole farm (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.* 817128 numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation ran for a total of 265 hours (11.04 days). This covered the treatment period (168 hours), a dispersion period to the EQS assessment after 240 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 25m x 25m squares using the same depth range as the treatment depth (i.e. 0 – 5 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 2010 (ID350/1) (Figure 5). A further set of simulations was performed over neap tides in 2021 (ID366) to confirm the adequacy of dispersion during the weakest tides (Figure 6).

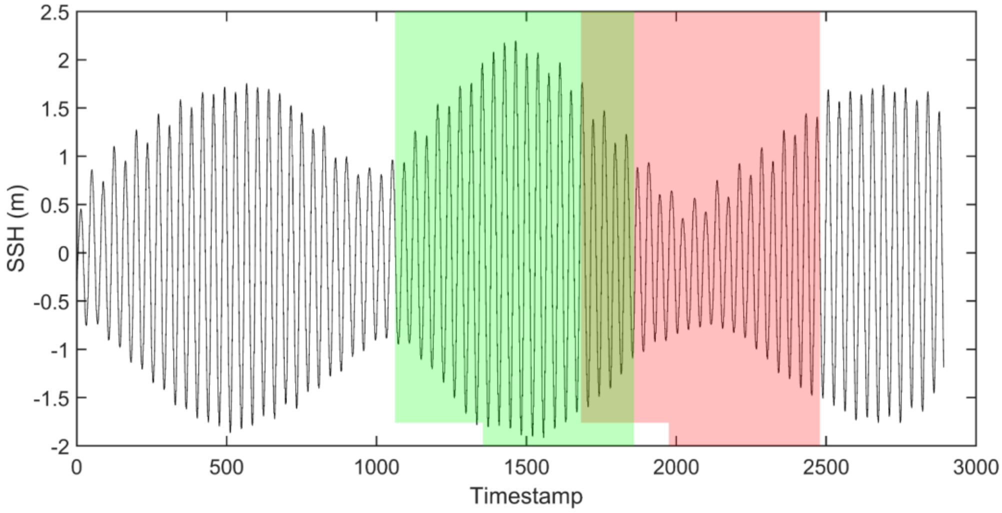

Figure 5. Sea surface height (SSH) at Muck from 8th April –18th May 2010 (ID350/ID351). Dispersion simulations were performed over periods of neap tides (red, start day 1st May 2010) and spring tides (green, start day 22nd April 2010)

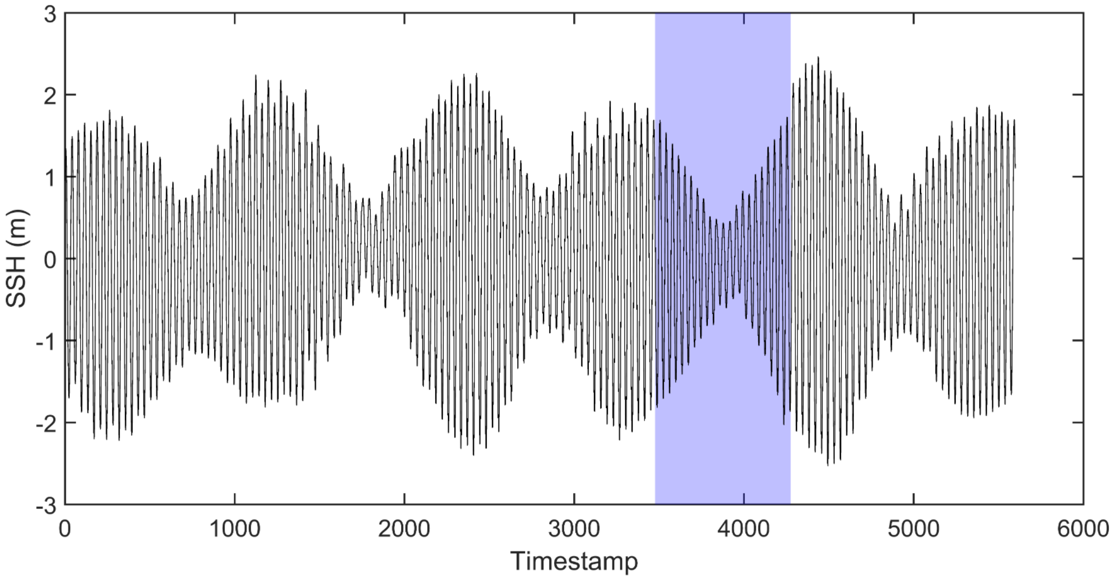

Figure 6. Sea surface height (SSH) at Muck from 27th January 2010 – 15th April 2021 (ID366). Dispersion simulations were performed over periods of neap tides (purple, start day 17th March 2021).

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	143200	780207	5	1.02	0
2	143295	780238	5	1.02	24
3	143169	780302	5	1.02	48
4	143264	780333	5	1.02	72
5	143138	780397	5	1.02	96
6	143233	780428	5	1.02	120
7	143107	780492	5	1.02	144
8	143202	780525	5	1.02	168

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

Set	Run No.	$T_{1/2}$ (h)	K_H	K_V	Start Time
Neap Tides, Start day = 23 (1st May 2010, ID350/351)					
Baseline	1	134.4	0.1	0.001	12:00
1	2	134.4	0.1	0.001	12:00 -6h
	3	134.4	0.1	0.001	12:00 -4h
	4	134.4	0.1	0.001	12:00 -2h
	5	134.4	0.1	0.001	12:00 +2h
	6	134.4	0.1	0.001	12:00 +4h
	7	134.4	0.1	0.001	12:00 +6h
2	8	213.6	0.1	0.001	12:00
	9	55.2	0.1	0.001	12:00
3	10	134.4	0.2	0.001	12:00
	11	134.4	0.05	0.001	12:00
	12	134.4	0.03	0.001	12:00
4	13	134.4	0.1	0.0025	12:00
	14	134.4	0.1	0.005	12:00
Spring Tides, Start day = 14 (22nd April 2010, ID350/351)					
5	15	134.4	0.1	0.001	12:00
	16	213.6	0.1	0.001	12:00
	17	55.2	0.1	0.001	12:00
6	18	134.4	0.2	0.001	12:00
	19	134.4	0.05	0.001	12:00
	20	134.4	0.03	0.001	12:00
7	21	134.4	0.1	0.0025	12:00
	22	134.4	0.1	0.005	12:00
Neap Tides, Start day = 49 (17th March 2021, ID366)					
8	23	134.4	0.1	0.001	12:00
	24	213.6	0.1	0.001	12:00
	25	55.2	0.1	0.001	12:00
9	26	134.4	0.2	0.001	12:00
	27	134.4	0.05	0.001	12:00
	28	134.4	0.03	0.001	12:00
10	29	134.4	0.1	0.0025	12:00
	30	134.4	0.1	0.005	12:00

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 16.7 cm s^{-1} was used from ID350 (Table 5) which was the current meter deployment closest to the site location and most representative of the currents at 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})	0.1675
Area of 160m pen (km^2)	0.002037
Distance from shore (km)	0.5
Mean water depth (m)	33.6
Treatment Depth (m)	5
Mixing zone ellipse area (km^2)	**0.264128**

For the 3-hour EQS assessment, the baseline runs for neap and spring tides (Runs 1 and 15 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 25m x 25m grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

2.6 Cumulative Modelling

As well as sensitivity analysis, cumulative bath modelling was also undertaken for Muck and near-by site, Rum, to check for any interaction between treatments. A proposed organic site by the Isle of Canna was not included in the cumulative modelling due to no azamethiphos consent being applied for. Table 6 shows details of the two sites used in the cumulative model runs.

Table 6. Details of sites included in cumulative modelling

	Muck	Rum
Company:	Mowi	Mowi
Site location:	NM 4304 8056	NG 4086 0300
Peak biomass (T):	4,069	2,500
No. of pens:	8	12
Pen dimensions:	160m circumference	120m circumference
Pen configuration:	2 x 4	2 x (2 x 3)

A treatment depth of 5 m was chosen as a realistic net depth during application of the medicine for the 120m circumference pens at Rum. Table 7 shows the total treatment mass used at each site. A total mass of 13.661 kg of azamethiphos was released from the cumulative modelling simulations. At Rum, 4 pens were treated per day, as the current Azamethiphos consent allows. These were released 3 hours apart. The initial mass released per pen was set as the consented 3 hr limit for Rum, 458.43g. The EQS was then applied, as before, 72 hours after the final treatments.

Table 7. Total mass of azamethiphos released from sites during the cumulative modelling simulations

Site	24 hr mass released (kg)	Total mass released (kg)
Muck	1.02	8.16
Rum	1.834	5.501

Dispersion simulations were performed over neap and spring tides from April and May 2010 (Figure 5, ID350/ID351) with parameters matching that of the baseline run performed for Muck only. The pen locations and medicine release times are listed in Table 8.

The start time of the treatments were adjusted accordingly to allow for both sites to complete treatment at the same time on the same day so that the EQS could be applied. The simulations ran for 265 hours. This covered the treatment period (168 hours), a dispersion period to the EQS assessment after 240 hours (72 hours after the final treatment), and an extra 25 hours to check for chance concentration peaks, as done previously. The simulation used ~ 1.4 million numerical particles in total, each particle representing 10 mg of azamethiphos.

Table 8. Pen locations and treatment schedule for the cumulative modelling runs.

Pen	Site	Easting	Northing	Treatment Mass (kg)	Release Time Schedule (h)
1	Muck	143200	780207	1.02	0
2	Muck	143295	780238	1.02	24
3	Muck	143169	780302	1.02	48
4	Muck	143264	780333	1.02	72
5	Muck	143138	780397	1.02	96
6	Muck	143233	780428	1.02	120
7	Muck	143107	780492	1.02	144
8	Muck	143202	780525	1.02	168
1	Rum	140875	803046	0.458	111
2	Rum	140938	803005	0.458	114
3	Rum	141001	802964	0.458	117
4	Rum	141127	802883	0.458	120
5	Rum	141190	802842	0.458	135
6	Rum	141252	802801	0.458	138
7	Rum	140916	803109	0.458	141
8	Rum	140979	803068	0.458	144
9	Rum	141042	803027	0.458	159
10	Rum	141167	802946	0.458	162
11	Rum	141230	802905	0.458	165
12	Rum	141293	802864	0.458	168

2.7 Diffusion Coefficients

Selection of the horizontal diffusion parameter, K_H, was guided by dye releases conducted near the Muck site by Anderson Marine Surveys Ltd on 20th September 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 gave a mean horizontal diffusivity of 0.03 $m^2 s^{-1}$. 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.

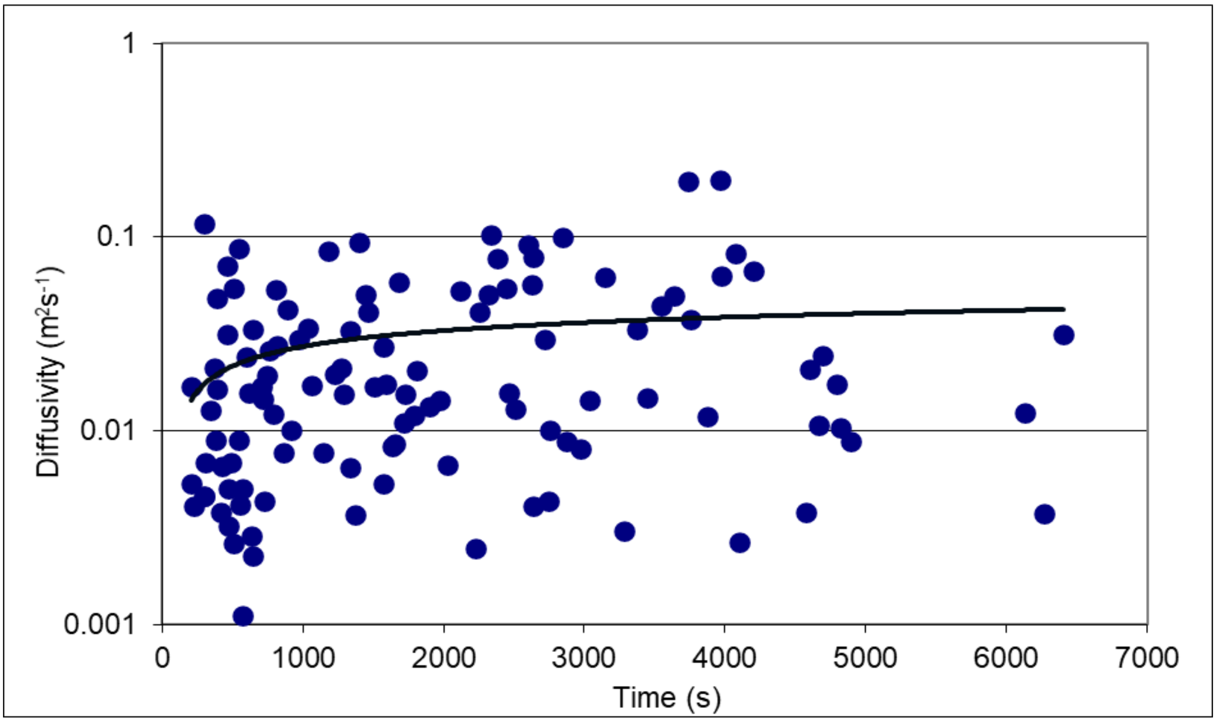

Figure 7. Estimated horizontal diffusivity ($m^2 s^{-1}$) from dye release experiments at Muck on 20th September 2017. The mean diffusivity was 0.03 $m^2 s^{-1}$.

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.

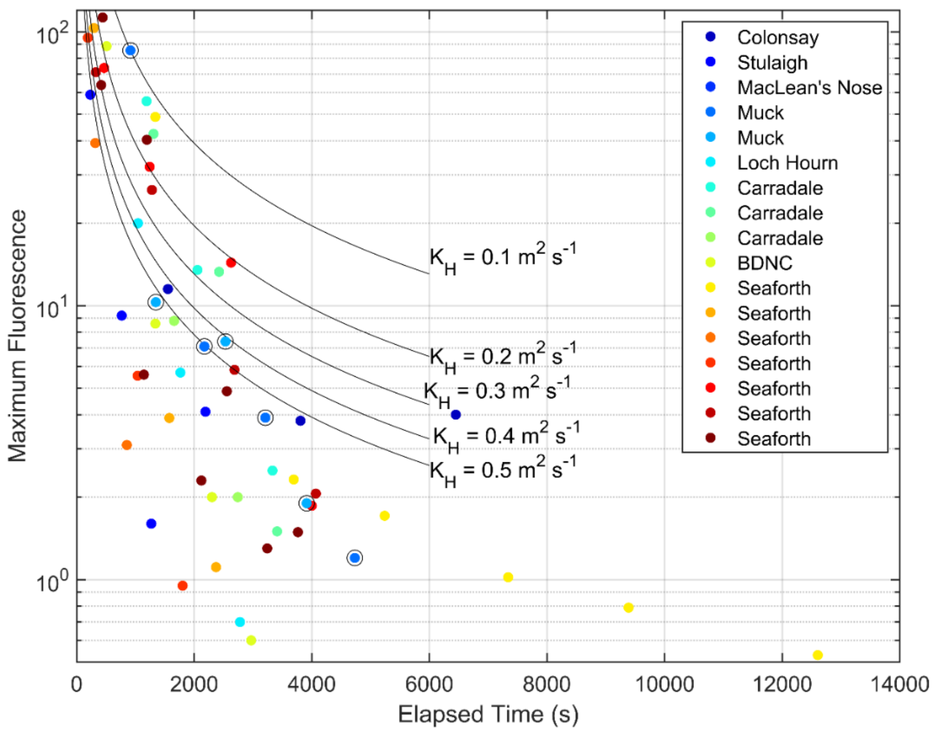

Figure 8. Maximum fluorescence measured following dye releases at a number of Mowi sites in Scotland. The data points from Muck are circled. The black lines indicate the rate at which the maximum concentration would fall at different horizontal diffusivities.

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, May 2010 (ID350/1)

A standard treatment of 8 x 160m 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, resulted in a treatment mass per pen of azamethiphos of 1.02 kg, a daily (24-h) release of 1.02 kg and a total treatment release of 8.16 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 days treatment is discharged, discrete patches of medicine are evident from the first days treatment release. The maximum concentration at this time was about 100 µg/L, due to the release of the second treatment. After 72 hours, as the fourth treatment was discharged, discrete patches of medicine from the third treatment are still evident, but the patches of medicine from the first and second day 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. After 120 hours, the sixth treatment was released, patches from the fifth treatment release were still evident but patches from the days previous to this had dispersed rapidly and were again down to concentrations of the same order as the EQS (0.04 µg/L). The maximum concentration at this time was still at around 100 µg/L due to the release of the sixth treatment.

The treatment schedule completed after 168 hours (7 days). At this stage, the medicine released on earlier days has already dispersed west. 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 168 hours, the treatment patches were rapidly dispersed and concentrations rapidly fell away below the EQS. Remnants of medicine remain north-west and south-west off the Isle of Muck but at concentrations below the MAC.

The time series of maximum concentration from this simulation is shown in Figure 10. The 8 peaks in concentration of ~100 µg/L following each treatment event over the first 8 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 h (5.6 days) was used. The maximum concentration seventy-two hours after the final treatment (time = 240 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 1 km^2 during treatment on Day 3, 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 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 environmental quality standards 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.

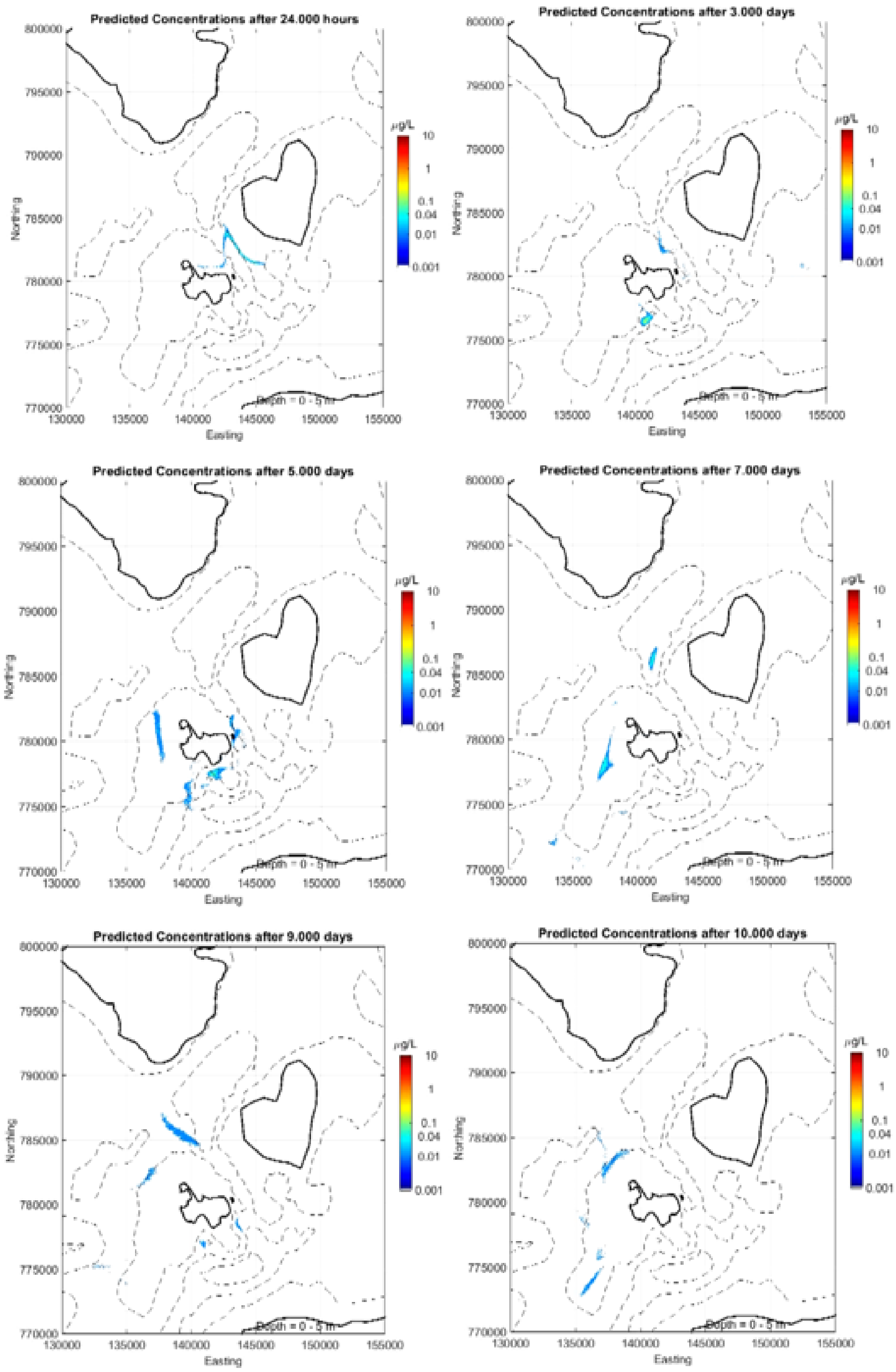

Figure 9. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 72 hours (top right), 120 hours (middle left), 168 hours (middle right), 216 hours (bottom left) and 240 hours (bottom right).

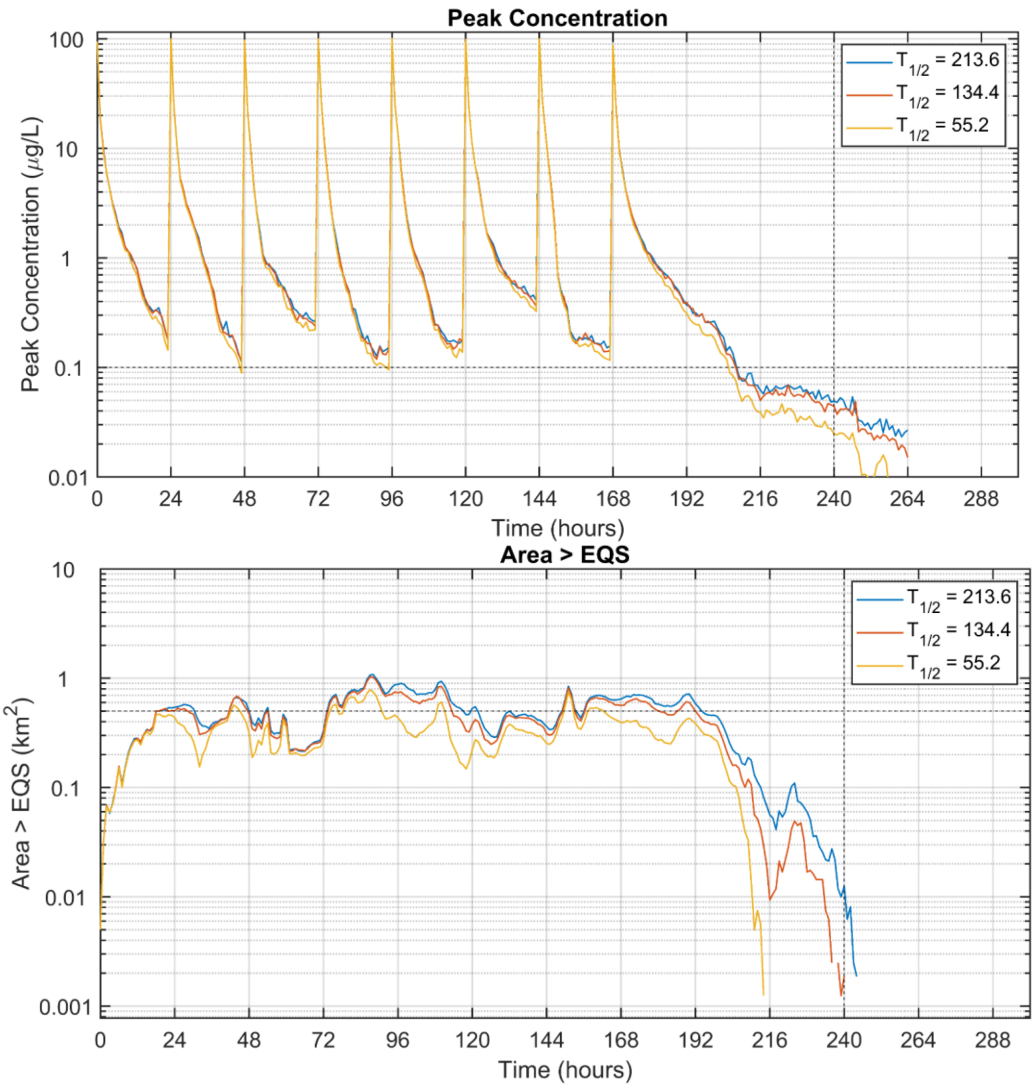

Figure 10. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tide with varying medicine half-life ($T_{1/2}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L and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

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 1 km^2 following treatment on Day 3, 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 standard runs was K_H = 0.1 m^2 s^{-1}.

Simulations were also performed with lower and higher values of K_H, specifically $K_H = 0.2\ m^2\ s^{-1}$, $K_H = 0.05\ m^2\ s^{-1}$ and $K_H = 0.03\ m^2\ s^{-1}$ (Table 4).

The time series of maximum concentration and area exceeding the EQS are shown in Figure 11. The time series confirm that the MAC was not exceeded after 240 hours (72 hours after the final treatment) with either $K_H = 0.2$ or $0.05\ m^2\ s^{-1}$. But there is however a very minor concentration failure with $K_H = 0.03\ m^2\ s^{-1}$. We believe that this latter value is very low, and not supported by the diffusion values derived from the peak measured concentration (Figure 8). The area limit of $0.5\ km^2$ was comfortably met in all cases.

Similarly, sensitivity to the vertical diffusion coefficient, K_V, was tested (Figure 12). 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.

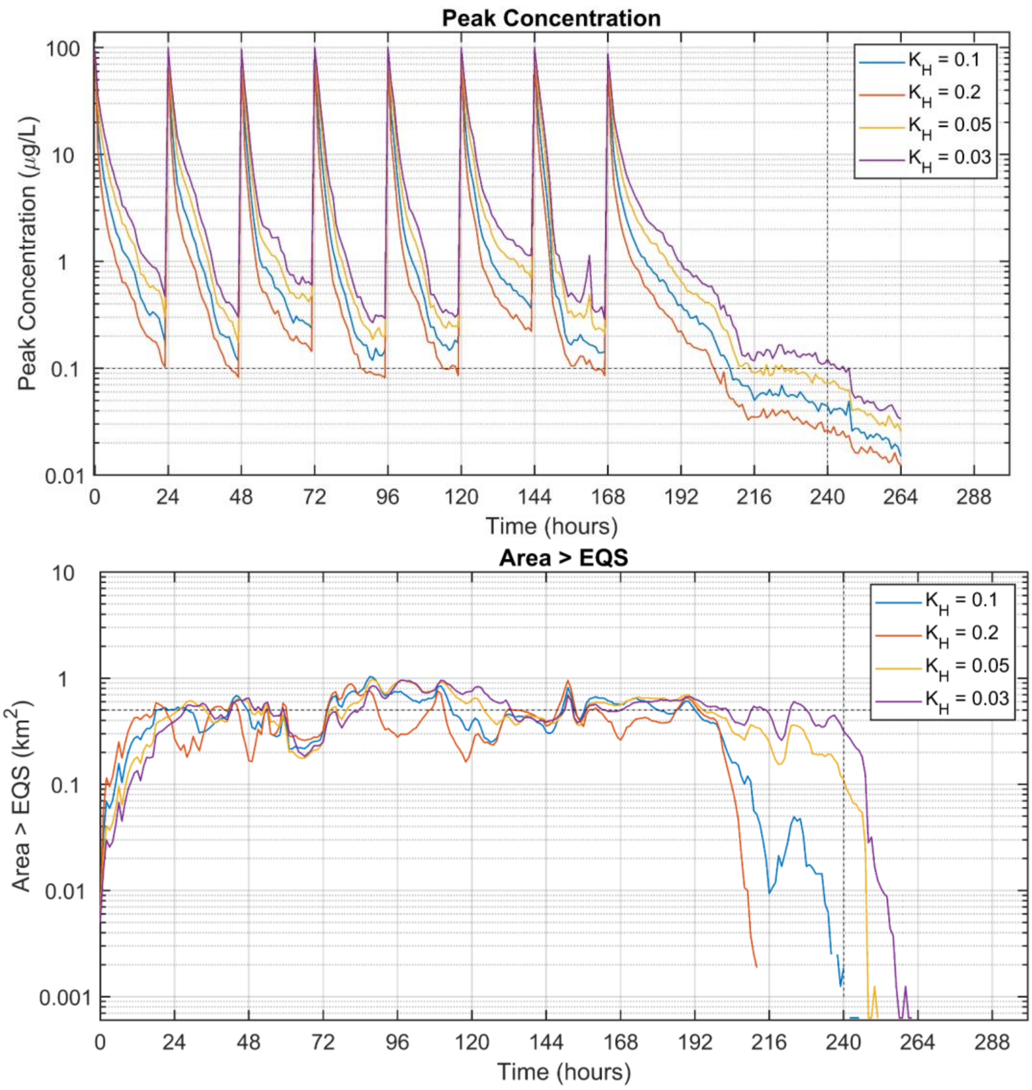

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient K_H ($m^2\ s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L and 0.5 km² are indicated by the horizontal dashed lines.

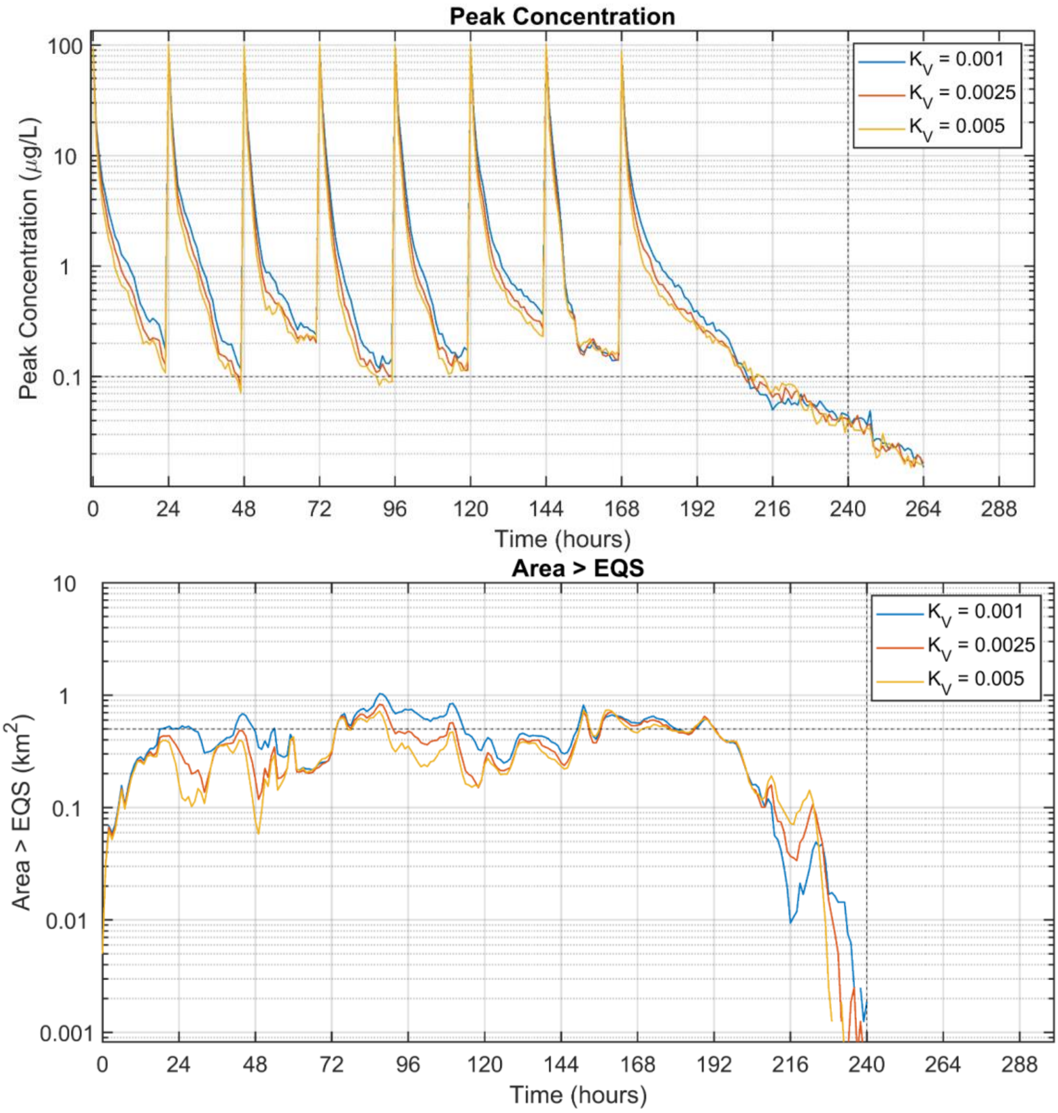

Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient K_V (m^2 s^{-1}). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L 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 variability including some obvious concentration peaks in the -2hr and -4hr runs which are potentially down to an artefact in the model (Figure 13). However, this only causes two very minor MAC failures. A half-life of 134.4 hours was used in these runs which is thought to still be conservative, so a second batch of time sensitivity model runs (Table 9) were performed using a more realistic half-life of 55.2 hours to confirm that the time sensitivity runs all pass the MAC condition comfortably (Figure 14).

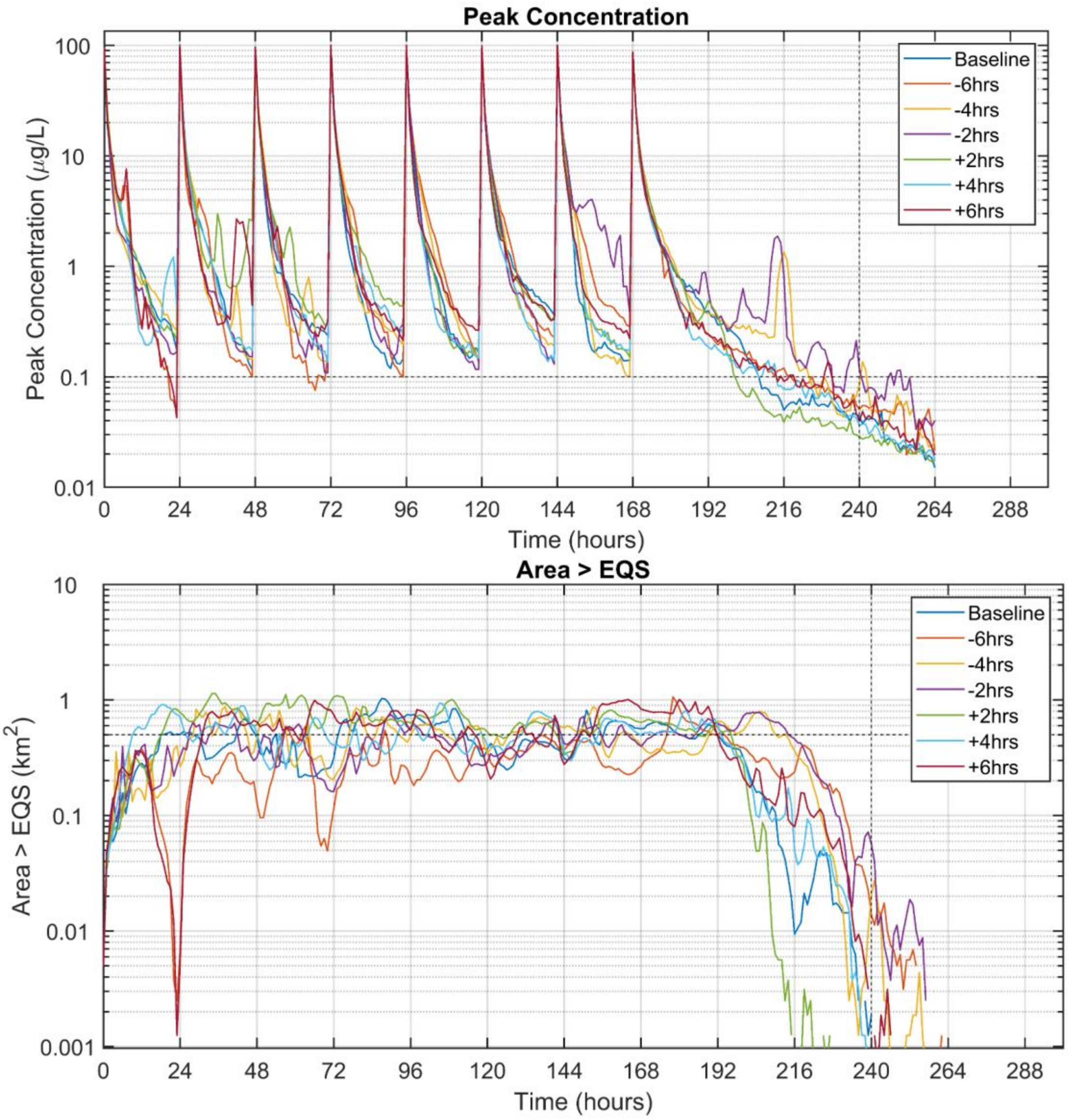

Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 12 h). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

Table 9. Second set of time sensitivity dispersion model simulations for the treatment of 8 pens at Muck.

Set	Run No.	T 1/2 (h)	Kh	Kv	Start Time
Neap Tides, Start day = 23 (1st May 2010, ID351)					
11	31	55.2	0.1	0.001	12:00 -6h
	32	55.2	0.1	0.001	12:00 -4h
	33	55.2	0.1	0.001	12:00 -2h
	34	55.2	0.1	0.001	12:00 +2h
	35	55.2	0.1	0.001	12:00 +4h
	36	55.2	0.1	0.001	12:00 +6h

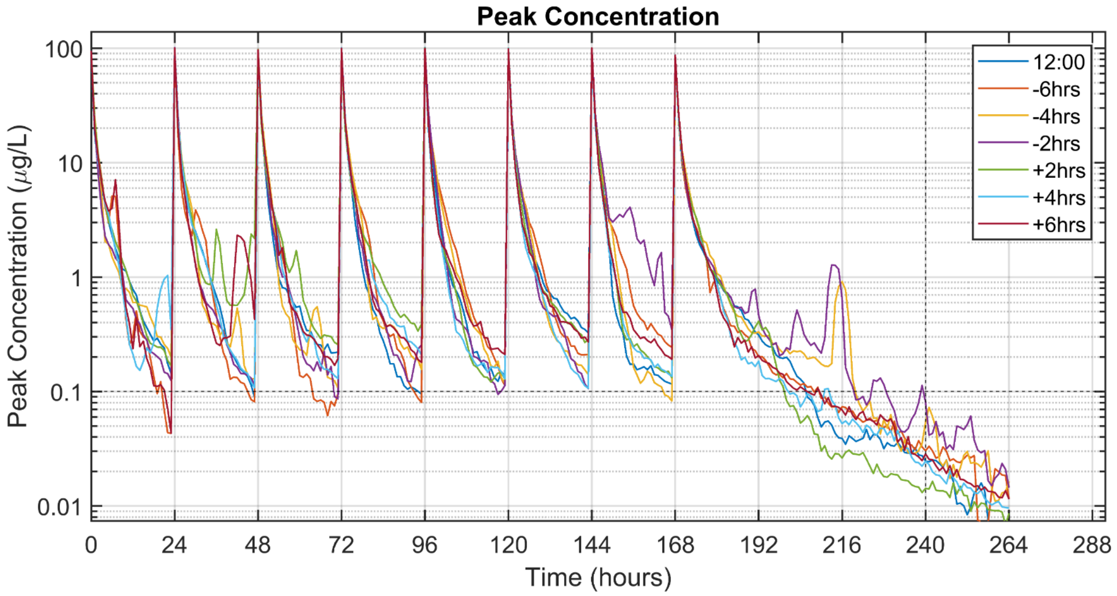

Figure 14. Time series of maximum concentration from the eleventh set of model runs (Table 9). The model was run over neap tides with varying release times, relative to time 12:00 which is used as standard in all other sensitivity runs. The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L is indicated by the horizontal dashed line.

3.5 Dispersion during Spring Tides, April 2010 (ID350/1)

Dispersion simulations were carried out during modelled spring tides in April 2010 (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 1.02 kg of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were achieved (Figure 15).

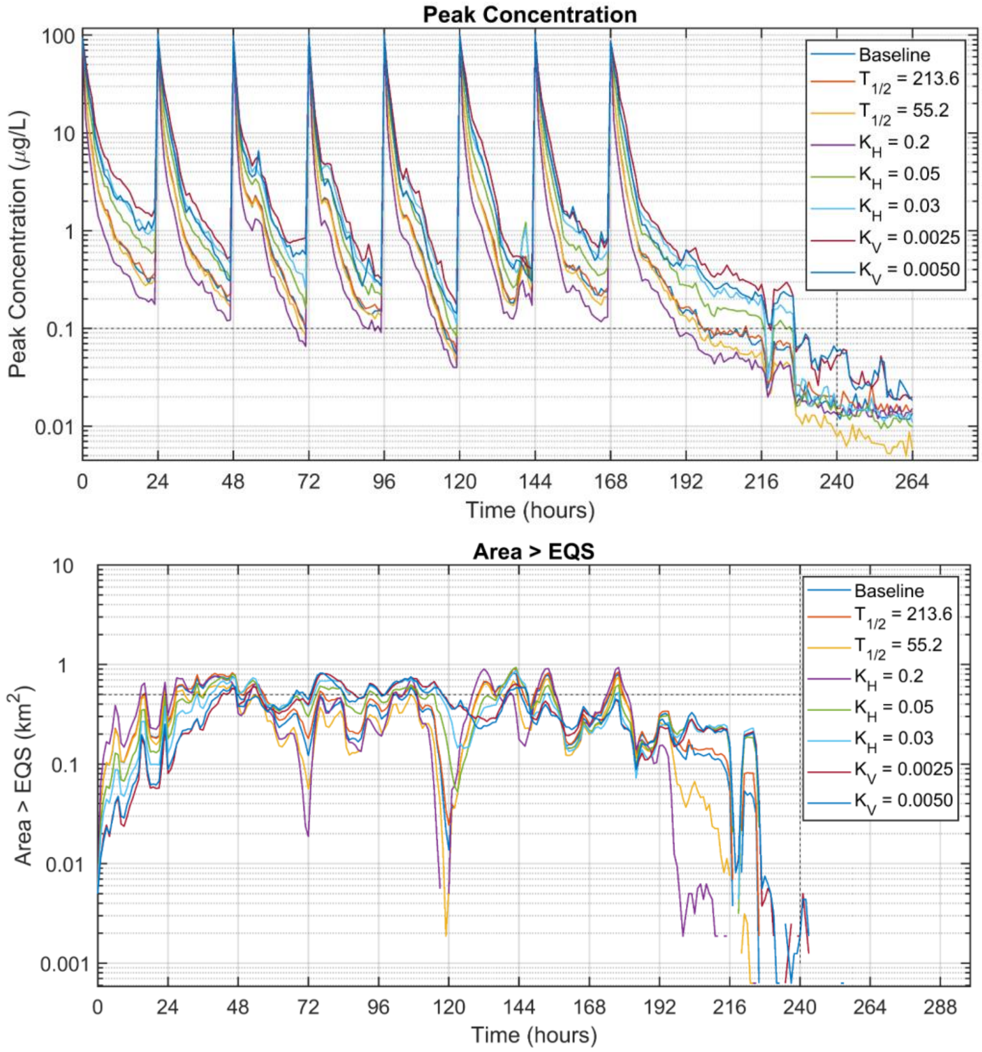

Figure 15. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient K_H ($m^2 s^{-2}$) and vertical diffusion coefficient K_V ($m^2 s^{-2}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.6 Dispersion During Neap Tides, March 2021 (ID366)

A further set of dispersion simulations during modelled neap tides in March 2021 were carried out (Figure 6), repeating the main set carried out for neap tides in May 2010 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 1.02 kg of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved (Figure 16). These simulations demonstrate again that the modelled treatment regime will comfortably meet the EQS criteria.

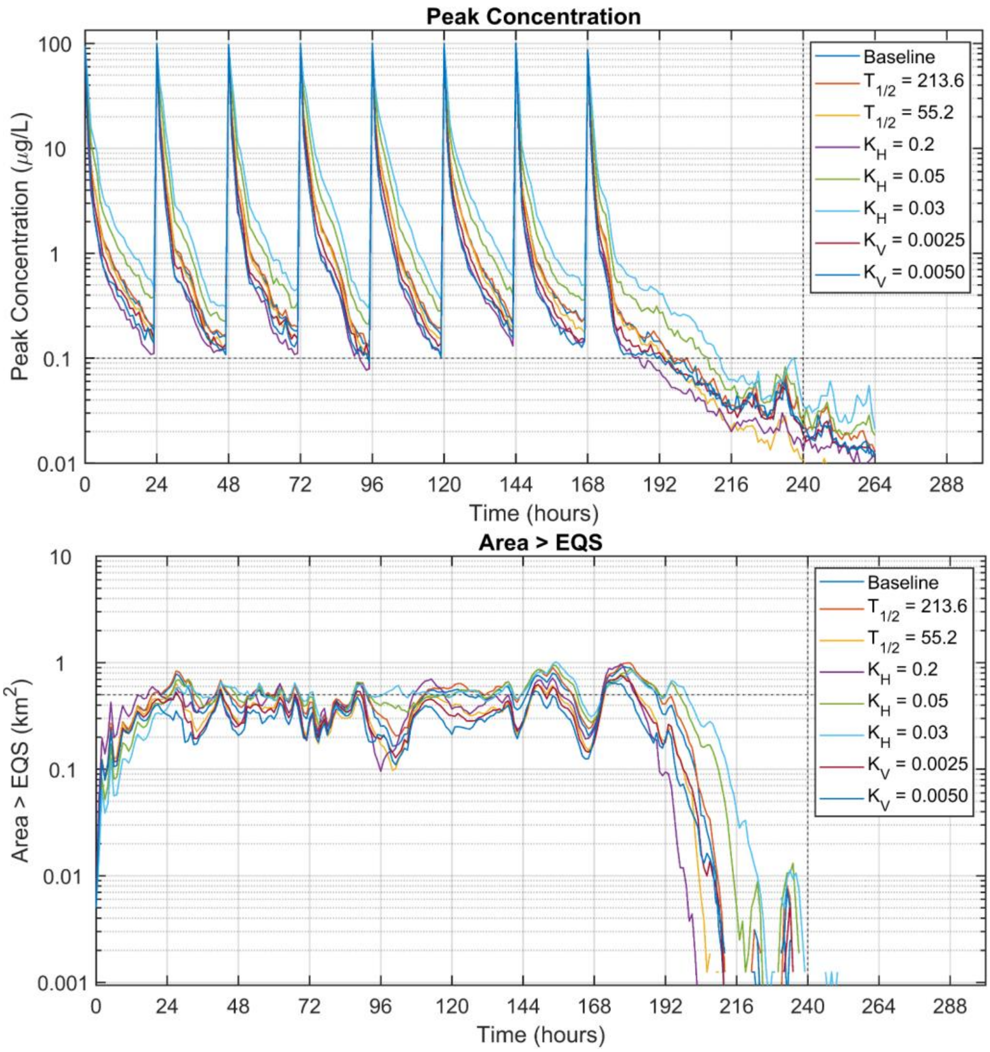

Figure 16. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, nineth and tenth set of model runs (Table 4). The model was run at neap tides in March 2021 with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient K_H ($m^2 s^{-2}$) and vertical diffusion coefficient K_V ($m^2 s^{-2}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 g/L and 0.5 km^2 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 16.75 cm s^{-1} was used from ID350 (Table 1) which was thought to be a representative value for the surface 0-5m layer at Muck. 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 1st May 2010) are shown in Figure 17. For each treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone

(0.26 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 22nd April 2010), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 18). 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 1.02 kg of azamethiphos from each of the eight proposed 160m pens at Muck should not breach the 3-hour Environmental Quality Standard.

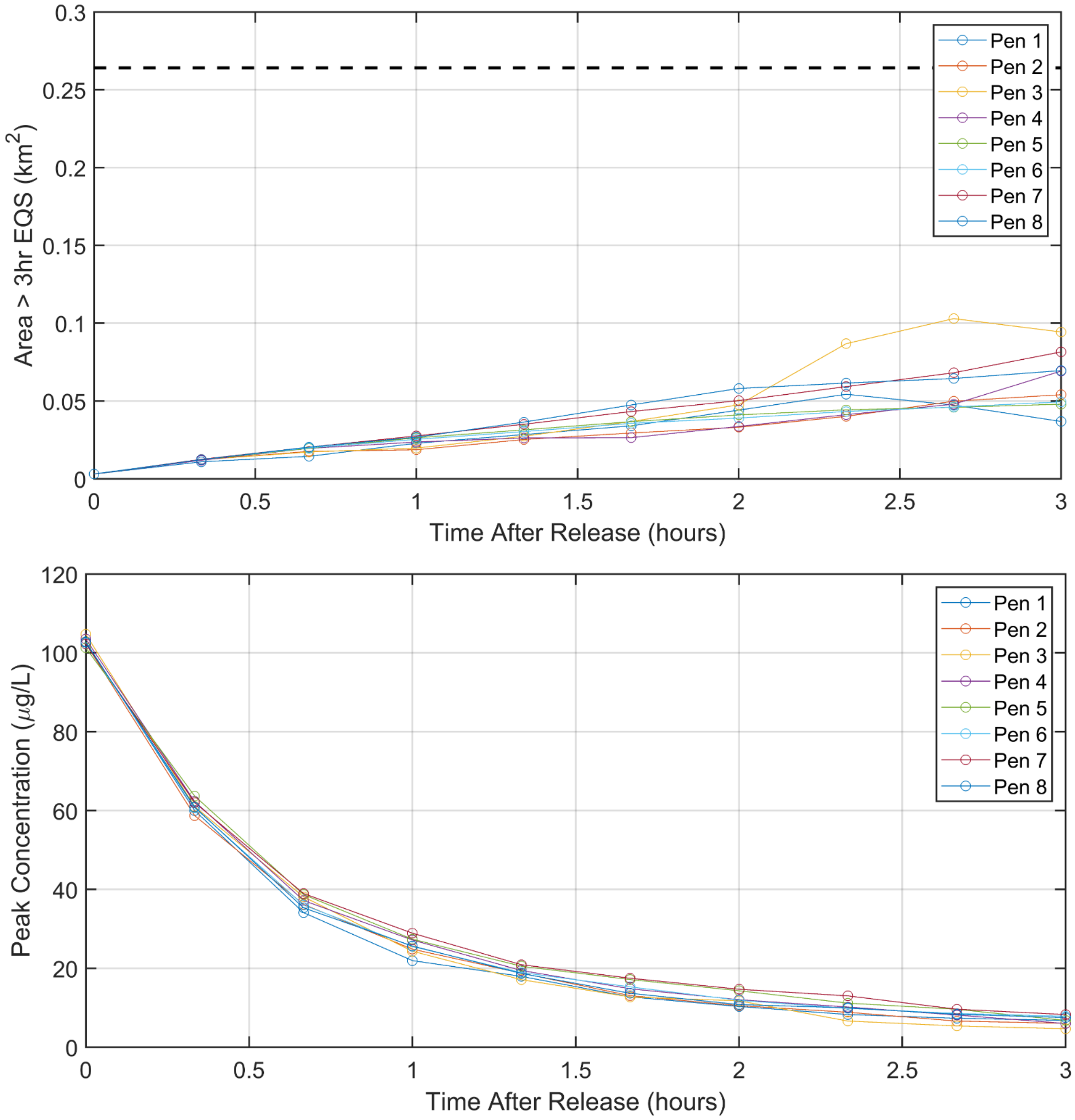

Figure 17. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area indicated (---).

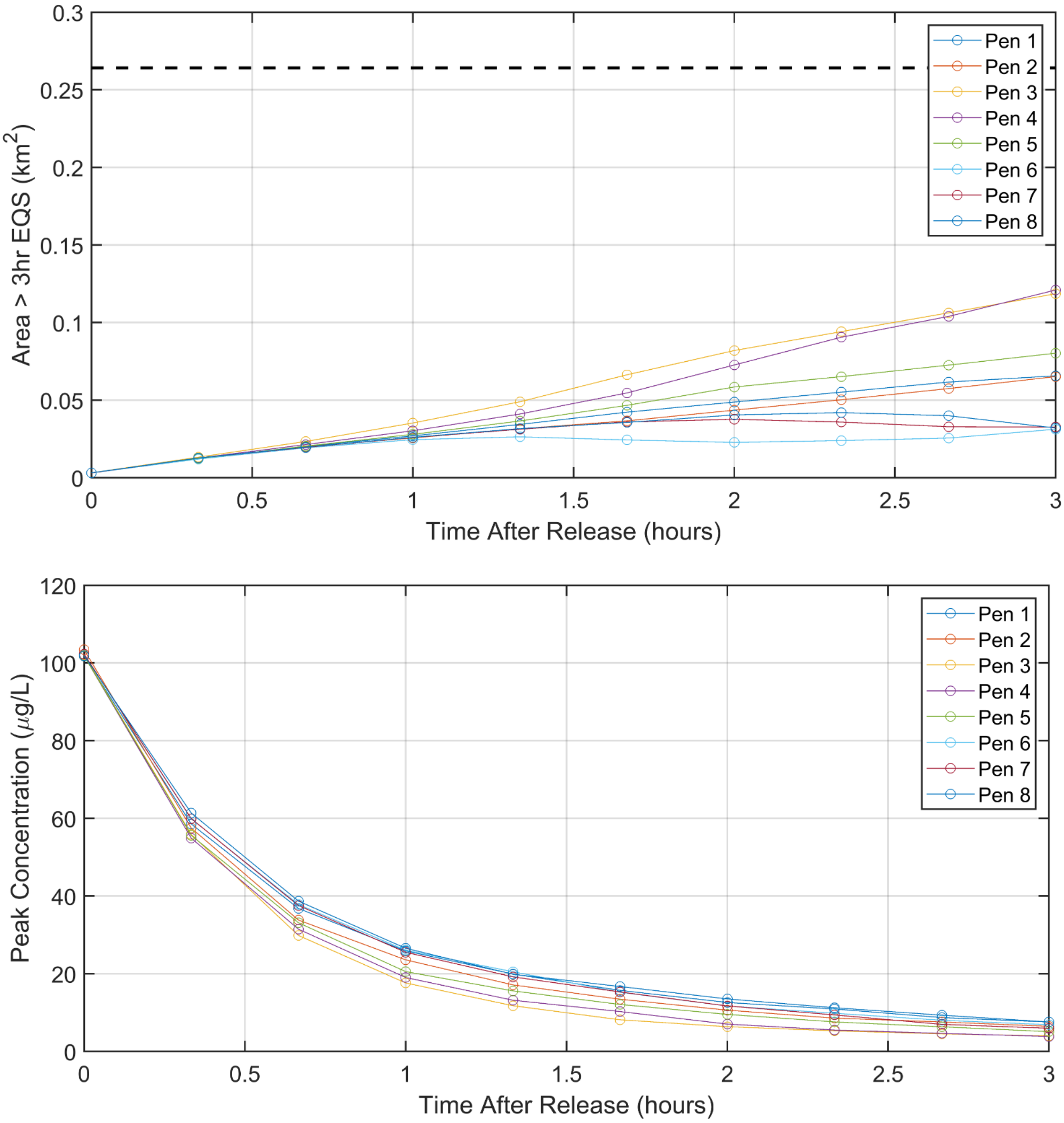

Figure 18. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area indicated (---).

3.8 Cumulative Modelling

Figure 19 shows the dispersion simulation with the neap tide. After 24 hours, as the second days treatment was discharged at Muck, patches of medicine are evident. The maximum concentration at this time was ~100 µg/L, due to the release of the second treatment. After 5 days, the first 6 treatments have already been released from Muck and the first four treatments released from Rum. At this time, patches of medicine are evident from the previous days releases but they have rapidly dispersed and are already down to concentration levels of the same degree as the MAC (0.04 µg/L). After 7 days, the treatments have completed at both

Muck and Rum, patches of medicine are now evident between Muck and Rum and the peak concentration is still at ~100 µg due to the final release from each site. At the EQS time of 10 days (72 hours after the final treatments), patches of medicine are still evident, however concentrations have decreased rapidly. It is clear from the dispersion simulation that the medicine released from Muck does not interact with any of the discharged medicine patches from Rum.

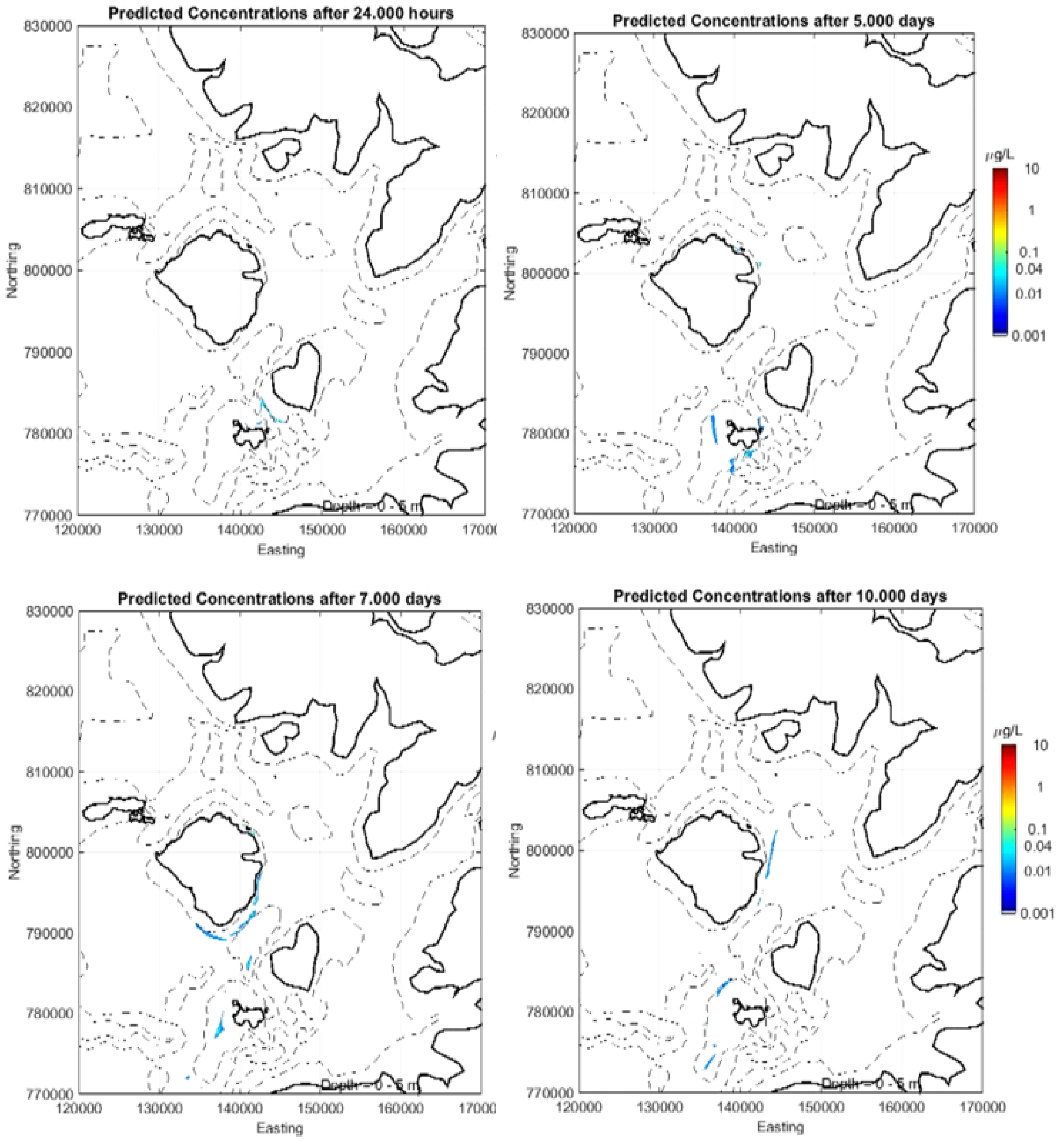

Figure 19. Dispersion simulation over neap tide at Muck and its neighbouring site Rum, following the treatment schedule described in Table 8. Start day = 23. The pens for each site are marked (○).

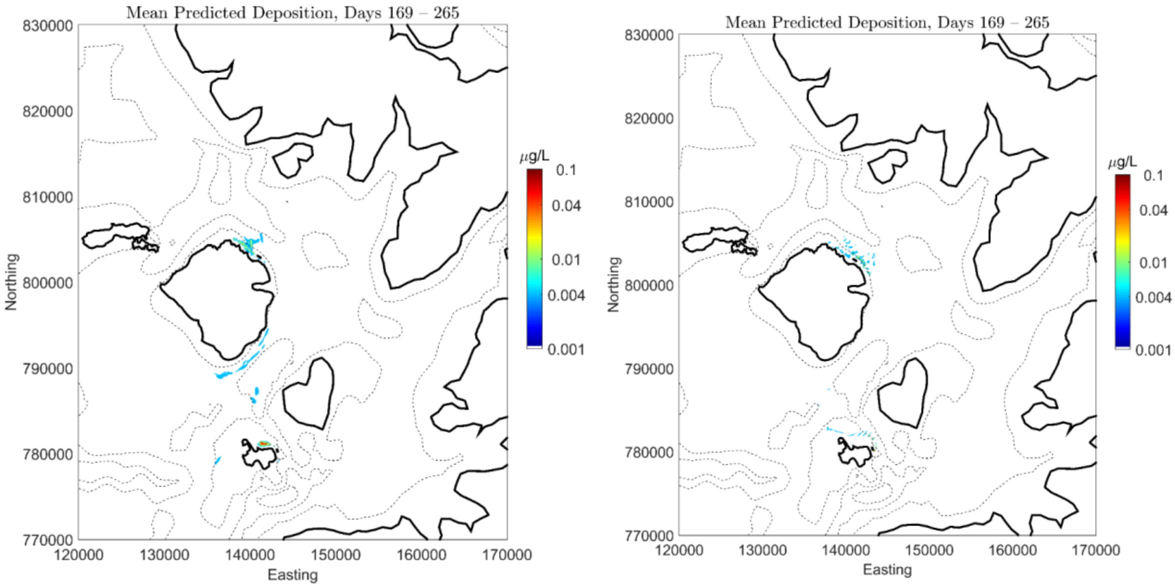

*Figure 20. Mean predicted concentrations over the last 96 hours of the treatment scenario described in Table 8, over neap tide (left) and spring tide (right)***.**

Figure 20 shows the mean concentration over the last 96 hours of the cumulative modelling simulations performed over both neap and spring tides. Time series of peak concentration and area exceeding the EQS for both sites over neap and spring tides are shown in Figure 21 and Figure 22 respectively. Site-specific modelling has been undertaken at Rum (Mowi Scotland 2020) to inspect the medicine dispersion in more detail.

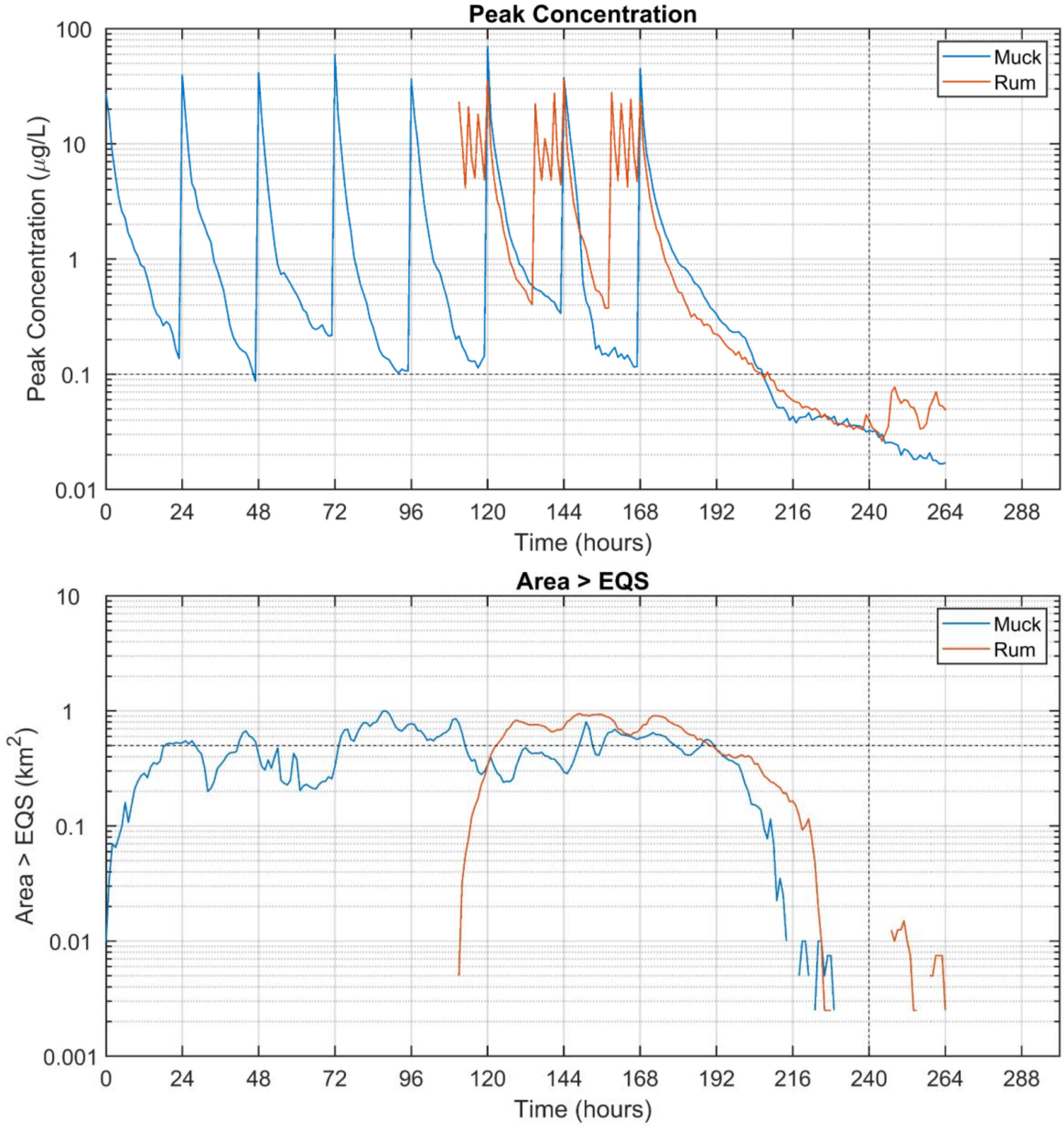

Figure 21. Time series of maximum concentration (top) and area exceeding the EQS (bottom) for the cumulative modelling of all sites over neap tide (STARTDAY = 23). The MAC and area limits 72 hours after the final treatment (Time = 240 hours) of 0.1 µg/L and 0.5 km² respectively are indicated by the horizontal dashed lines.

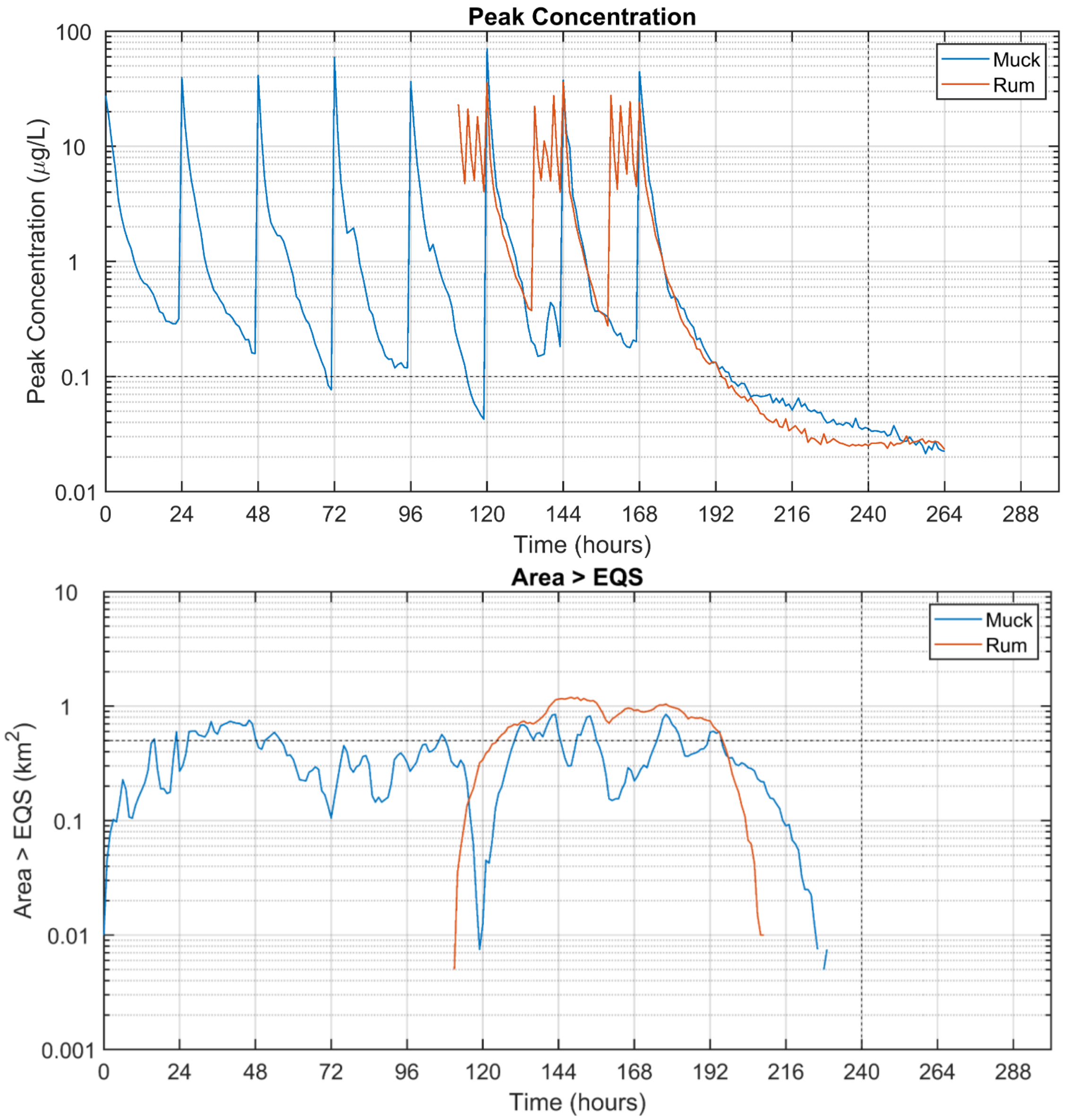

Figure 22. Time series of maximum concentration (top) and area exceeding the EQS (bottom) for the cumulative modelling of all sites over spring tide (STARTDAY = 14). The MAC and area limits 72 hours after the final treatment (Time = 240 hours) of 0.1 µg/L and 0.5 km² respectively are indicated by the horizontal dashed lines.

4 SUMMARY AND CONCLUSIONS

A total of 40 dispersion simulations have been performed to assess whether bath treatments at Muck salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1.02 kg of azamethiphos for treatment, resulting in a total discharge over 8 days of 8.16 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 10.

Table 10. Summary of Results

Site Details	
Site Name:	Muck
Site Location:	Isle of Muck
Peak Biomass (T):	4,069
Pen Details	
Number of Pens:	8
Pen Dimensions:	160m circumference
Working Depth (m):	15
Pen Group Configuration:	2 x 4
Azamethiphos	
Recommended 3hr Consent (kg):	1.02
Recommended 24hr Consent (kg):	1.02

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 1.02 kg, should consistently comply with the EQS. The peak concentration during the baseline simulation after 240 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 some sensitivity testing, the EQS and MAC criteria were met, apart from one simulation using a horizontal diffusion coefficient of 0.03 where a very minor fail was observed, however, the parameters used in these runs are known to be highly conservative. Further simulations over a neap tide from 2021 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 1.02 kg of azamethiphos can be safely discharged without breaching the MAC or EQS.

The cumulative modelling that was undertaken for Muck and neighbouring site Rum indicated that if both sites were treated simultaneously, there will be no interaction between the medicine plumes.

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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