Sconser Quarry, Caol Mor

Bath Medicine Dispersion Modelling Report

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Mowi Scotland Limited
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CONTENTS

List of Figures

List of Tables

EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Sconser Quarry salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1.021 kg of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) for treatment, resulting in a daily release of the same amount and a total discharge over 7 days of 7.150 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 1.021 kg of azamethiphos, should comfortably comply with the EQS. The peak concentration during the baseline simulation after 216 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 are also presented that demonstrate compliance with the 3-hour EQS at both spring and neap tides. Cumulative modelling is presented addressing the effects of simultaneous treatments at seven sites in the Caol Mor region.

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:	Sconser Quarry
Site Location:	Caol Mor
Peak Biomass (T):	2,500
Pen Details	
Number of Pens:	7
Pen Dimensions:	160m circumference
Working Depth (m):	16
Pen Group Configuration:	2 x 3 + 1
Azamethiphos	
Recommended 3hr Consent (kg):	1.021
Recommended 24hr Consent (kg):	1.021

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 Sconser Quarry, Caol Mor (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 June 2019 (SEPA, 2019).

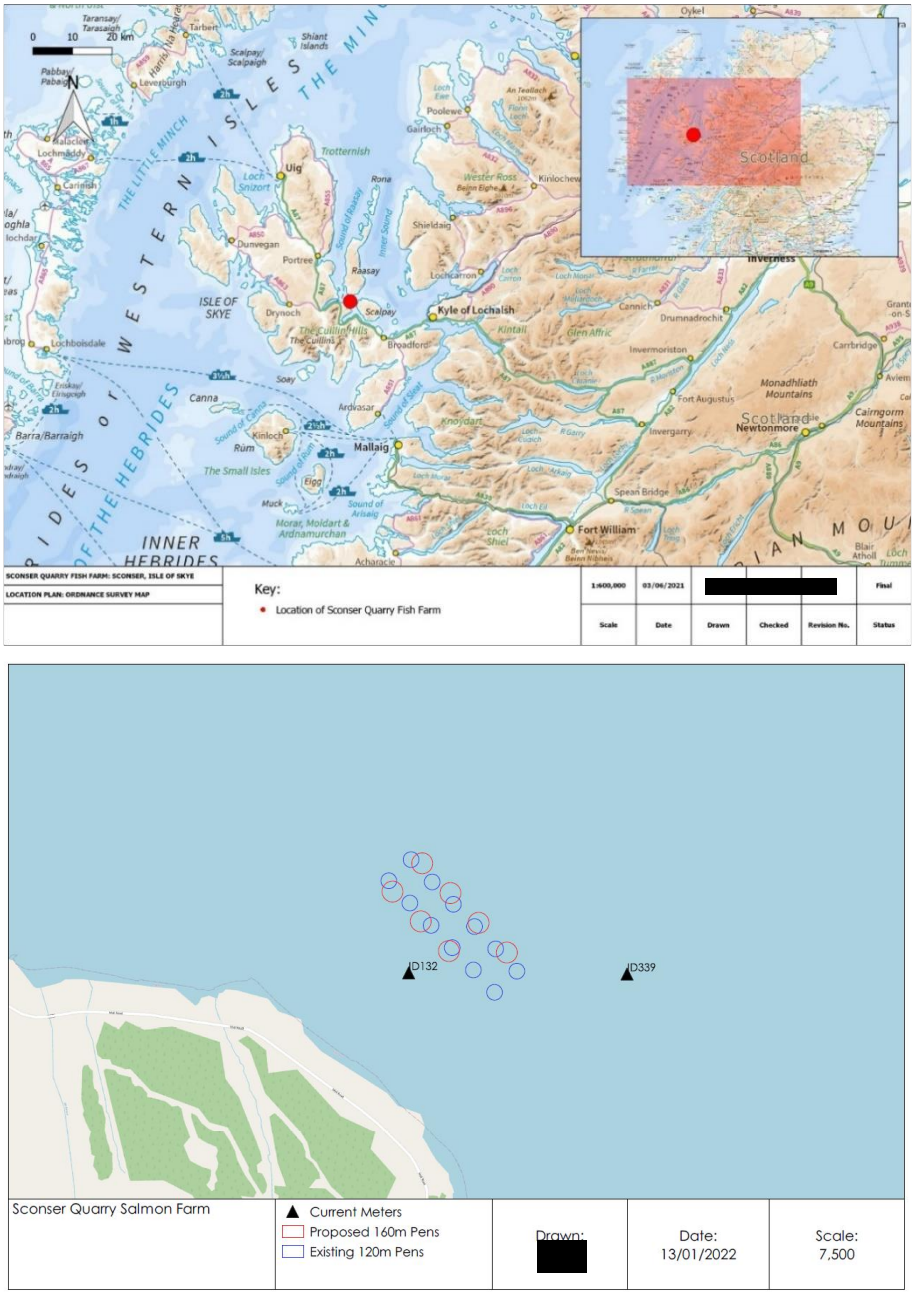

*Figure 1. Location of Sconser Quarry salmon farm (top) and the location of the ADCP deployments (▲) relative to the proposed pen positions (**o**).*

1.1 Site Details

The site is situated off the East coast of the Isle of Skye (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:	Sconser Quarry	
Site Location:	Caol Mor	
Peak Biomass (T):	2,500	
Proposed Feed Load (T/yr)	6,387.5	
Proposed Treatment Use:	Azamethiphos	
Pen Details		
Group Location:	NG56313224	
Number of Pens:	7	
Pen Dimensions:	160m circumference	
Grid Matrix (m):	100	
Working Depth (m):	12	
Pen Group Configuration:	2 x 3 + 1	
Pen Group Orientation (°G):	125	
Pen Group Distance to Shore (km):	0.4	
Water Depth at Site (m):	35	
Hydrographic Data		
	ID132	**ID339**
Current Meter Position:	156216E 832119N	156749E 832116N
Depth at Deployment Position (m):	39.4	39.3
Surface Bin Centre Height Above Bed (m):	31.72	31.71
Middle Bin Centre Height Above Seabed (m):	21.72	26.71
Bottom Bin Centre Height Above Bed (m):	2.72	3.71
Duration of Record (days):	62	81
Start of Record:	05-Dec-2016	17-Apr-2020
End of Record:	06-Feb-2017	08-Jul-2020
Current Meter Averaging Interval (min):	20	20
Magnetic Correction to Grid North:	-0.492	0.120

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, 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 (e.g. 72 hours after the final treatment) and compared with relevant Environmental Quality Standards (EQS). Here, we have modelled the dispersion of azamethiphos following a treatment scenario at Sconser Quarry to demonstrate the quantities of medicine that can disperse safely in the environment.

2.1 Model Domain and Boundary Conditions

The unstructured mesh used in the modelling was adapted from the East Coast of Lewis and Harris (ECLH) mesh developed by Marine Scotland Science (Marine Scotland, 2016). This domain (Figure 2) provided wide coverage around our area of interest off the east coast of Skye. Model resolution was enhanced in the Caol Mor region, particularly around the Mowi

sites at Sconser Quarry, Maol Ban and Cairidh (Figure 3). The spatial resolution of the model varied from 25m in some inshore waters to 5km along the open boundary. In total, the model consisted of 44,600 nodes and 83,538 triangular elements.

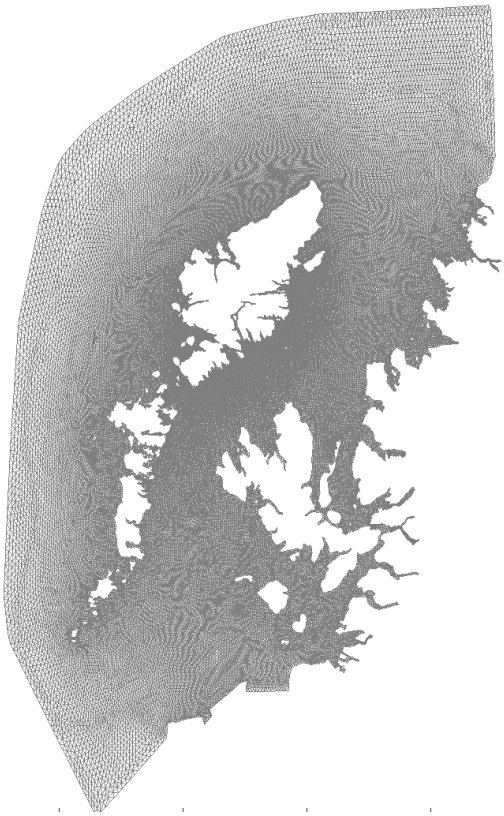

Figure 2. The mesh and domain of the modelling study, adapted from the East Coast of Lewis and Harris (ECLH) mesh (Marine Scotland, 2016).

Water depths in the model were based on the original ECLH model, but were modified in the Sound of Raasay area using bathymetry from the UK Hydrographic Office portal (UKHO, 2022), which contains high resolution data in the inshore waters around the islands of Raasay and Scalpay. These data were interpolated onto the node locations in Sound of Raasay region around the farm sites (Figure 4).

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

The model was run in 3D mode with 10 sigma layers evenly distributed over the water depth. Climatological river flow data, taken from the ECLH climatological runs (Marine Scotland, 2016) were used. In all, 155 rivers are included in the ECLH domain, with two entering the domain in the Coal Mor region, with discharge locations into Loch Ainort and Loch Sligachan (Figure 3).

Full details of the calibration and validation of the hydrodynamic model are given in the Hydrodynamic Model Description (Mowi Scotland Ltd, 2022).

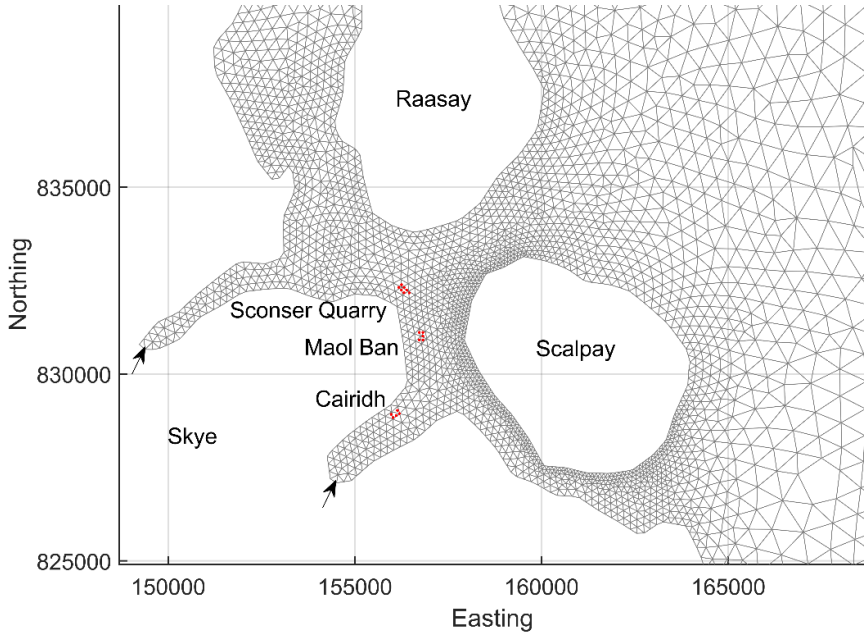

Figure 3. The unstructured mesh around the Sconser Quarry and other Caol Mor sites in the modified model grid, with the proposed pen locations indicated (•). Local freshwater discharges were input at the locations indicated (→).

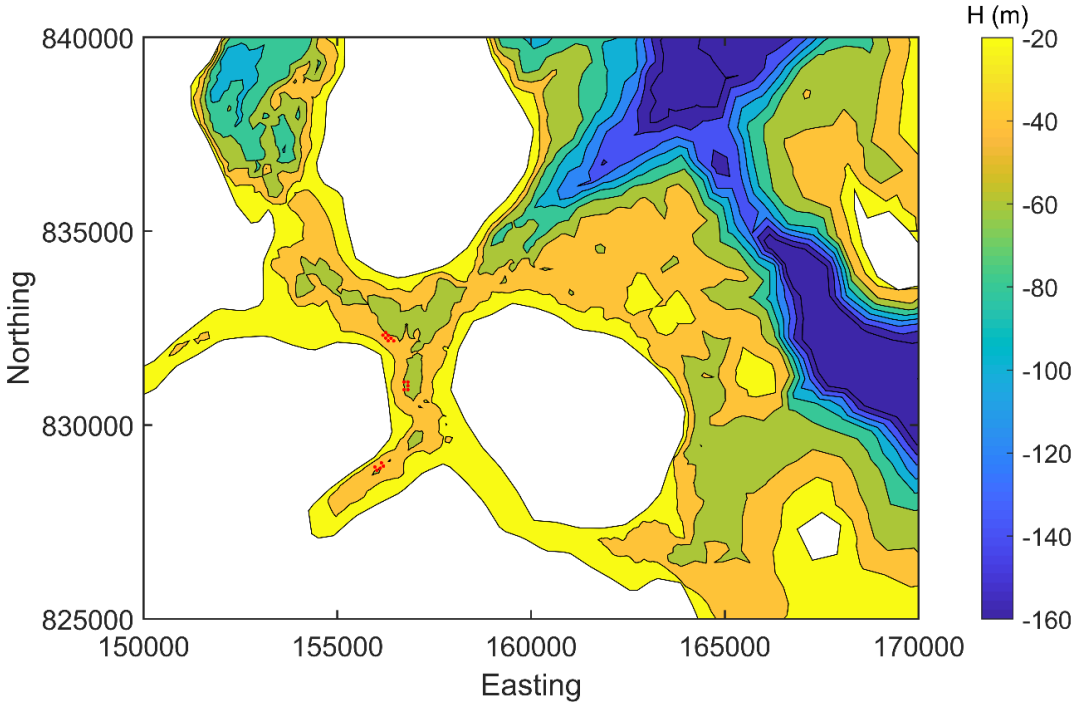

Figure 4. Localised bathymetry (H, m) around the Caol Mor sites in the modified mesh. The proposed pen locations indicated (•).

2.2 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 ten 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 7.15 kg of azamethiphos released during treatment of the whole farm (7 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 714,987 numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation ran for a total of 241 hours (10 days). This covered the treatment period (144 hours), a dispersion period to the EQS assessment after 216 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 and provides consistent resolution and accuracy of calculated concentrations across the domain.

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;
(ii) The area (km^2) where the EQS was exceeded;

These results were used to assess whether the EQS or maximum allowable concentration (MAC) conditions were 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 2020 (ID339, Figure 5). The ID339 data are thought to better represent the regional oceanography than the near-shore deployment of ID132.

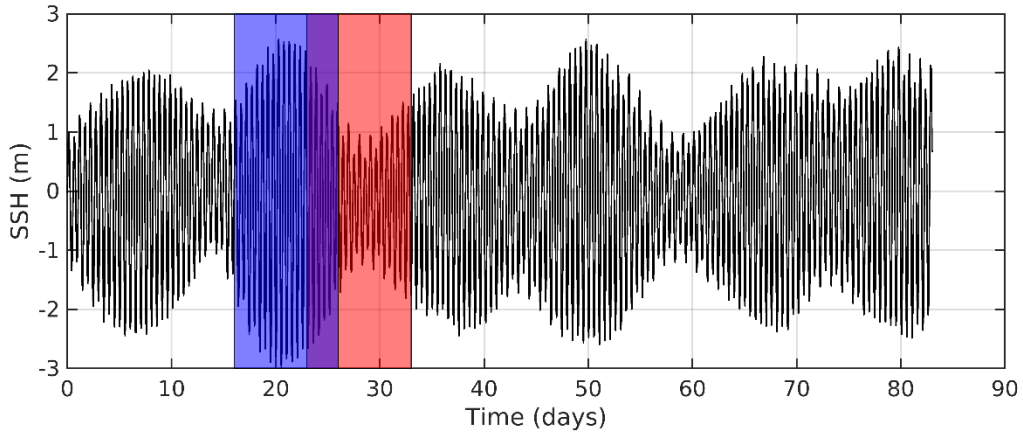

Figure 5. Modelled sea surface height (SSH) at Sconser Quarry from 17th April – 8th July 2020 (ID339). Dispersion simulations were performed over periods of neap tides (red, start day 9th May 2020) and spring tides (blue, start day 2nd May 2020)

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 5.

All simulations used the release schedule and quantities outlined in Table 3. In Runs 8 – 13 and 21 – 26, 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 treatments simulated by the dispersion model. The release time is relative to the start of the neap or spring period highlighted in Figure 5, Figure 5 and Figure 7 .

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (kg)	Release Time (hr)
1	156176	832317	5.0	1.021	0
2	156249	832386	5.0	1.021	24
3	156318	832313	5.0	1.021	48
4	156245	832245	5.0	1.021	72
5	156314	832172	5.0	1.021	96
6	156387	832241	5.0	1.021	120
7	156456	832168	5.0	1.021	168

Table 4. Dispersion simulation details for the treatment of 7 pens at Sconser Quarry. Values for the medicine half-life ($T_{1/2}$, h), horizontal diffusivity (K_H, $m^2\ s^{-1}$), vertical diffusivity (K_V, $m^2\ s^{-1}$) and the time of the first release relative to 00:00Z on 9th or 2nd May 2020 are shown.

Set	Run No.	$T_{1/2}$ (h)	K_H	K_v	Start Time
Neap Tides, Start day = 23 (9th May 2020, ID339)					
Baseline	1	134.4	0.1	0.001	00:00
1	2	213.6	0.1	0.001	00:00
	3	55.2	0.1	0.001	00:00
2	4	134.4	0.05	0.001	00:00
	5	134.4	0.20	0.001	00:00
	6	134.4	0.1	0.0025	00:00
	7	134.4	0.1	0.0050	00:00
3	8	134.4	0.1	0.001	00:00 -6h
	9	134.4	0.1	0.001	00:00 -4h
	10	134.4	0.1	0.001	00:00 -2h
	11	134.4	0.1	0.001	00:00 +2h
	12	134.4	0.1	0.001	00:00 +4h
	13	134.4	0.1	0.001	00:00 +6h
Spring Tides, Start day = 16 (2nd May 2020, ID339)					
5	14	134.4	0.1	0.001	00:00
6	15	213.6	0.1	0.001	00:00
	16	55.2	0.1	0.001	00:00
7	17	134.4	0.05	0.001	00:00
	18	134.4	0.20	0.001	00:00
	19	134.4	0.1	0.0025	00:00
	20	134.4	0.1	0.0050	00:00
8	21	134.4	0.1	0.001	00:00 -6h
	22	134.4	0.1	0.001	00:00 -4h
	23	134.4	0.1	0.001	00:00 -2h
	24	134.4	0.1	0.001	00:00 +2h
	25	134.4	0.1	0.001	00:00 +4h
	26	134.4	0.1	0.001	00:00 +6h

2.4 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, 2021). 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 7.6 cm s^{-1} was used from ID132 (Table 1) which was the current meter deployment closest to the site location and most

representative of the currents at the site. The parameter values used in the calculation of the 3-hour mixing zone ellipse area are shown in Table 4 (Run 1).

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})	0.076
Area of 160m pen (km^2)	0.002037
Distance from shore (km)	0.4
Mean water depth (m)	39
Treatment Depth (m)	5
Mixing zone ellipse area (km^2)	**0.119843**

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 25m x 25m grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

2.5 Cumulative Dispersion Simulations

Simulations of dispersion of azamethiphos from all local sites assuming simultaneous treatments were performed for spring and neap tides. Local salmon farms in the Caol Mor region are listed in Table 6. The consented quantities of azamethiphos, both 24-hour and where stipulated, 3-hour, are listed. For the three Mowi Caol Mor sites (Sconser Quarry, Maol ban and Cairidh), the quantities used in the modelling are the quantities being requested within applications currently being prepared for all three sites for submission in 2022.

Table 6. Details of salmon farms in the Caol Mor region and their associated biomass (MSB, tonnes), and 3-hour and 24-hour azamethiphos discharge consents. Camas na Sgainadin and Rubha An Inbhir were not included in the modelling (see text).

Site	Operator	NGR	MSB (T)	3h Consent	24h Consent	Status
Sconser Quarry	Mowi	NG56313224	2500	1021.0*	1021.0*	Active
Maol Ban	Mowi	NG56743110	2250	224.7*	447.7*	Active
Cairidh	Mowi	NG56102890	1800	177.4*	325.6*	Active
Scalpay	Mowi	NG64122873	2500	269.3	687.7	Active
Sconser	Mowi	NG53453415	1500	358.7	1382.4	Inactive
Camas na Sgainadin	*SSC*	*NG61522659*	*405*	*134.0*	*340.0*	*Inactive*
Rubha An Inbhir	*SSC*	*NG54684171*	*2222.6*	-	*286.5*	*Inactive*
Loch Portree	SSC	NG50604412	2021.7	-	137.5	Active
Portree Outer	SSC	NG51084457	2192	-	103.1	Active

** requested quantities, January 2022.*

Three sites listed in Table 6 are no longer active. Two of those, Camas na Sgainadin and Rubha An Inbhir, no longer have infrastructure present and were not included in the modelling. The site at Sconser has recently been closed, but was included in this modelling exercise.

The medicine releases included in the cumulative simulations are listed in Table 7. These releases were performed using standard parameter values (cf. Runs 1 and 14, Table 6) for both neap and spring tides. The quantities released were based on the 3-hour and 24-hour consent quantities. No more than the 3-hour consented mass was discharged during a single release. The schedule of releases was determined by how many 3-hour discharges could be accomplished without exceeding the 24-hour limit. Treatments were scheduled so that all farms finished treating after 144 hours, so that the EQS could be applied after 216 hours and incorporate treatments from all sites.

Table 7. Details of releases for the cumulative modelling including location (Easting, Northing), release time (hours after start of simulation) and the release mass (kg). The release masses are based on the 3-h and/or 24-h discharge consents for each site (Table 6).

Site	Pen	Easting	Northing	Release Time (h)	Mass (kg)
Sconser Quarry	1	156176	832317	0	1.0210
Sconser Quarry	2	156249	832386	24	1.0210
Sconser Quarry	3	156318	832313	48	1.0210
Sconser Quarry	4	156245	832245	72	1.0210
Sconser Quarry	5	156314	832172	96	1.0210
Sconser Quarry	6	156387	832241	120	1.0210
Sconser Quarry	7	156456	832168	144	1.0210
Cairidh	1	156139	829025	96	0.1774
Cairidh	2	156192	828940	117	0.1774
Cairidh	3	156108	828887	120	0.1774
Cairidh	4	156023	828834	141	0.1774
Cairidh	5	155970	828919	144	0.1774
Maol Ban	1	156722	831111	96	0.2247
Maol Ban	2	156822	831111	117	0.2247
Maol Ban	3	156822	831011	120	0.2247
Maol Ban	4	156822	830911	141	0.2247
Maol Ban	5	156722	830911	144	0.2247
Sconser	1	153450	834150	66	0.3587
Sconser	2	153450	834150	69	0.3587
Sconser	3	153450	834150	72	0.3587
Sconser	4	153450	834150	90	0.3587
Sconser	5	153450	834150	93	0.3587
Sconser	6	153450	834150	96	0.3587
Sconser	7	153450	834150	114	0.3587
Sconser	8	153450	834150	117	0.3587
Sconser	9	153450	834150	120	0.3587
Sconser	10	153450	834150	138	0.3587
Sconser	11	153450	834150	141	0.3587
Sconser	12	153450	834150	144	0.3587
Scalpay	1	164120	828730	21	0.2693
Scalpay	2	164120	828730	24	0.2693
Scalpay	3	164120	828730	45	0.2693
Scalpay	4	164120	828730	48	0.2693
Scalpay	5	164120	828730	69	0.2693
Scalpay	6	164120	828730	72	0.2693
Scalpay	7	164120	828730	93	0.2693

Scalpay	8	164120	828730	96	0.2693
Scalpay	9	164120	828730	117	0.2693
Scalpay	10	164120	828730	120	0.2693
Scalpay	11	164120	828730	141	0.2693
Scalpay	12	164120	828730	144	0.2693
Loch Portree	1	150600	844120	45	0.0688
Loch Portree	2	150600	844120	48	0.0688
Loch Portree	3	150600	844120	69	0.0688
Loch Portree	4	150600	844120	72	0.0688
Loch Portree	5	150600	844120	93	0.0688
Loch Portree	6	150600	844120	96	0.0688
Loch Portree	7	150600	844120	117	0.0688
Loch Portree	8	150600	844120	120	0.0688
Loch Portree	9	150600	844120	141	0.0688
Loch Portree	10	150600	844120	144	0.0688
Portree Outer	1	151080	844570	45	0.0516
Portree Outer	2	151080	844570	48	0.0516
Portree Outer	3	151080	844570	69	0.0516
Portree Outer	4	151080	844570	72	0.0516
Portree Outer	5	151080	844570	93	0.0516
Portree Outer	6	151080	844570	96	0.0516
Portree Outer	7	151080	844570	117	0.0516
Portree Outer	8	151080	844570	120	0.0516
Portree Outer	9	151080	844570	141	0.0516
Portree Outer	10	151080	844570	144	0.0516

Table 8. Details of cumulative dispersion simulations for the treatment of 61 pens in the Caol Mor region at neap and spring tides. Parameter values for the medicine half-life ($T_{1/2}$, h), horizontal diffusivity (K_H, m^2s^{-1}), vertical diffusivity (K_V, $m^2\ s^{-1}$) are shown.

Set	Run No.	$T_{1/2}$ (h)	K_H	K_v
Neap Tide, Start day = 23 (9th May 2020, ID339)				
9	27	134.4	0.1	0.001
Spring Tide, Start day = 16 (2nd May 2020, ID339)				
9	28	134.4	0.1	0.001

2.6 Diffusion Coefficients

Dye releases have not been undertaken in the Caol Mor region, but a number of releases have been conducted for Mowi Scotland Ltd in recent years in Scottish coastal waters to assess horizontal diffusivity at salmon farm sites. 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.

We have identified the maximum concentration measured in each post-release survey (each comprised of a number of individual transects) and plotted the maximum concentration against the nominal time for that survey (typically accurate to ±15 minutes). The results are shown in Figure 6. A nominal mixed depth of H = 5m was used (see also Dale et al., 2020).

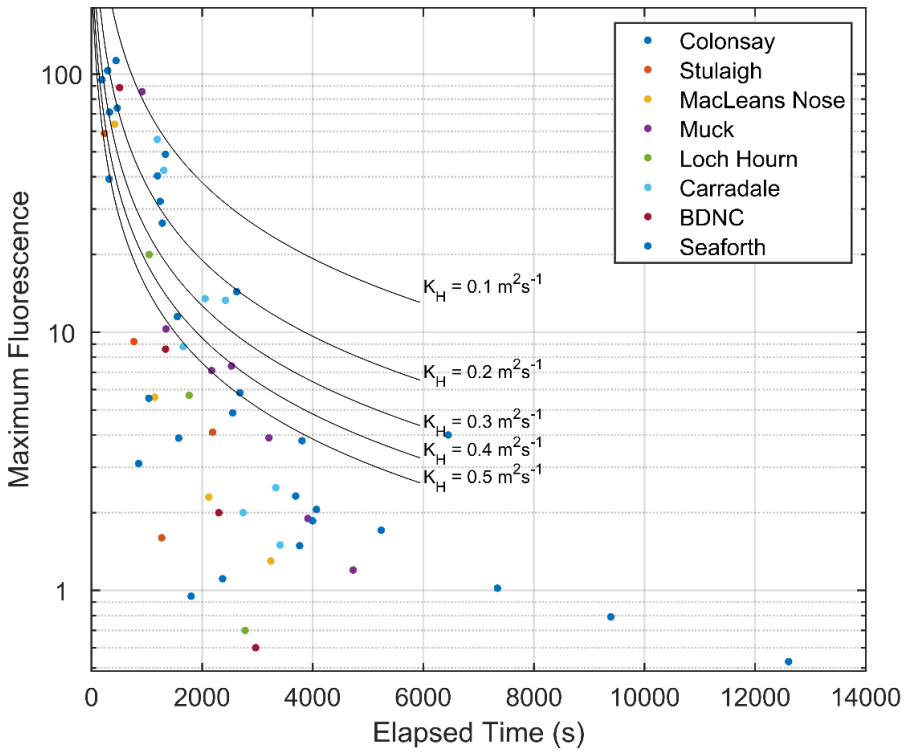

Figure 6. Maximum fluorescence measured following dye releases at a number of Mowi sites in Scotland. The black lines indicate the rate at which the maximum concentration would fall at different horizontal diffusivities.

The results strongly support the notion that horizontal diffusivity in the Scottish marine environment is substantially 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 most data thus far collected do not 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.

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 2020

A standard treatment of 7 x 160m pens, with a reduced net depth of 5.0 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 1.021 kg, a daily (24-h) release of 1.021 kg and a total treatment release of 7.147 kg over 144 hours. The dispersion of the medicine during and following treatment from Run 1, at neap tide in May 2020, is illustrated in Figure 7. After 24 hours, as the second days treatment was 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 first three treatments are still evident, but have already dispersed and are 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 first five treatment releases are not individually identifiable, but concentrations were typically around or below the maximum allowable concentration (MAC) of 0.1 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 144 hours (6 days). At this stage, the medicine released on earlier days had already dispersed north-eastwards into the Sound of Raasay. 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 144 hours, all treatment patches dispersed and concentrations rapidly fell away below the EQS, with typical values of about 0.01 µg/L.

The time series of maximum concentration from the simulation is shown in Figure 8. The 7 peaks in concentration of ~100 µg/L following each treatment event over the first 7 days are evident. Following the final treatment after 144 hours, the maximum concentration fell steadily away (Figure 8). A default half-life of 134.4 h (5.6 days) was used. The maximum concentration seventy-two hours after the final treatment (time = 216 hours) was well below the MAC of 0.1 µg/L.

The area where the EQS of 0.04 µg/L was exceeded peaked at about 1.2 km^2 during treatment on Day 6, 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 7 and Figure 8).

These results indicate that, at neap tide 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.

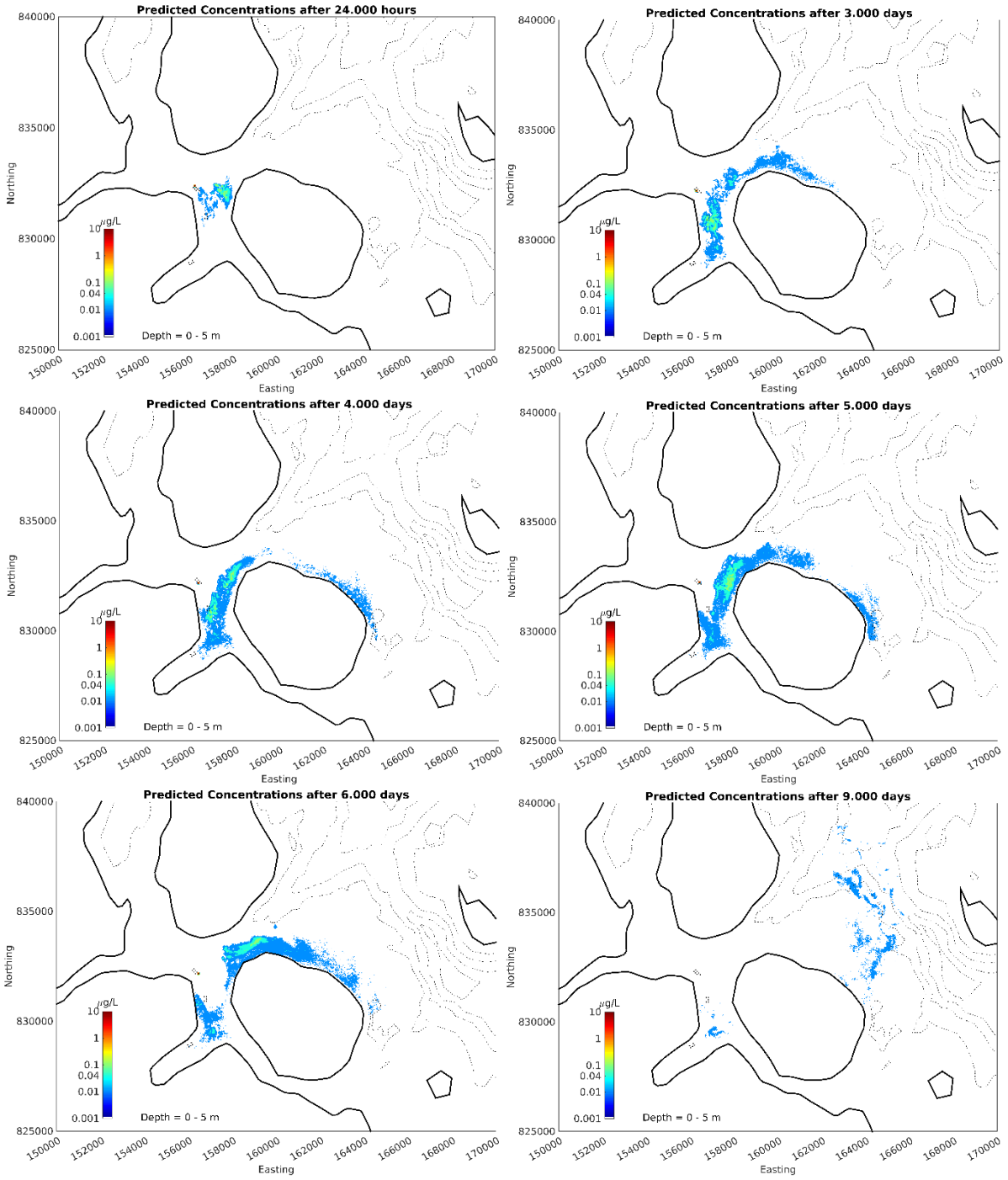

Figure 7. Predicted concentration fields for the baseline dispersion simulation (Run 1, Table 4) at neap tides after 24 hours (top left), 72 hours (top right), 96 hours (middle left), 120 hours (middle right), 144 hours (bottom left) and 216 hours (bottom right).

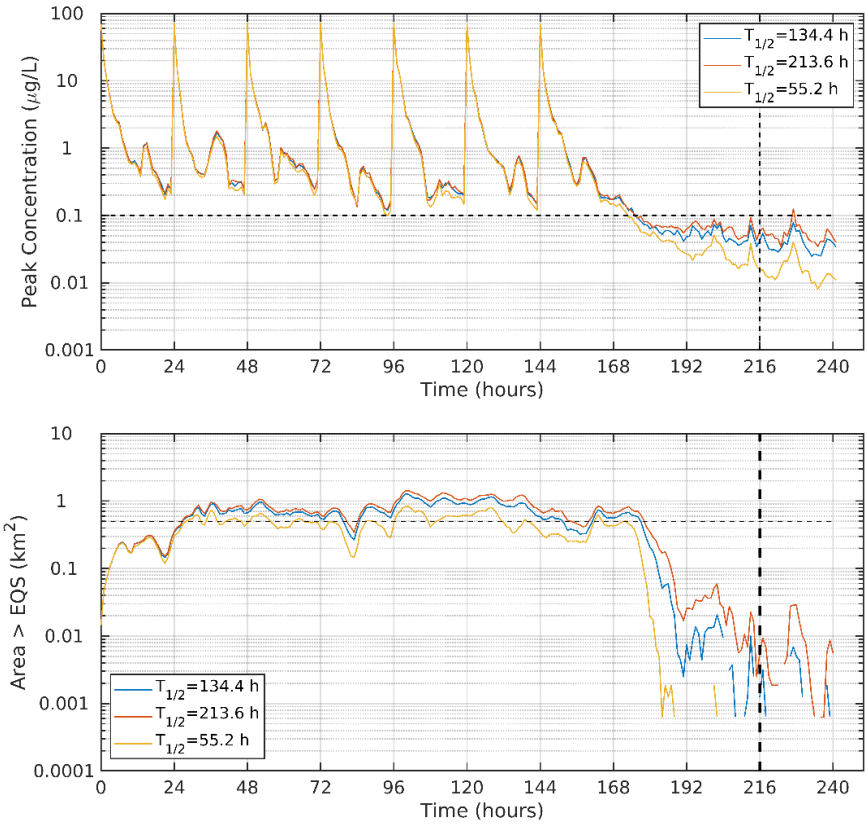

Figure 8. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tide with varying medicine half-life ($T_{1/2}$). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 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 half-lives of 5.6 days and 2.3 days (134.4h and 55.2h, Figure 8). With the very long half-life of 8.9 days, the peak concentration briefly and marginally exceeded 0.1 µg/L after 228 hours (Figure 8) but this half-life is no longer considered a realistic timescale of the breakdown of azamethiphos in seawater (Veterinary Medicines Directorate, 2020). The area where the EQS of 0.04 µg/L was exceeded peaked at about 1.3 km^2 following treatment on Day 6, but had fallen well below 0.5 km^2, for all simulated half-lives, within 72 hours of the final treatment (Figure 8). 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 = 0.05 m^2 s^{-1} and K_H = 0.20 m^2 s^{-1} (Table 4). The standard vertical diffusivity was K_V = 0.001 m^2 s^{-1} with additional simulations performed with K_V = 0.0025 m^2 s^{-1} and K_V = 0.0050 m^2 s^{-1}.

The time series of maximum concentration and area exceeding the EQS are shown in Figure 9. The time series confirm that the MAC was not exceeded after 216 hours (72 hours after the final treatment) with either K_H = 0.05 or 0.20 m^2 s^{-1}. 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. 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 lower peak concentrations and a smaller area where the EQS was exceeded.

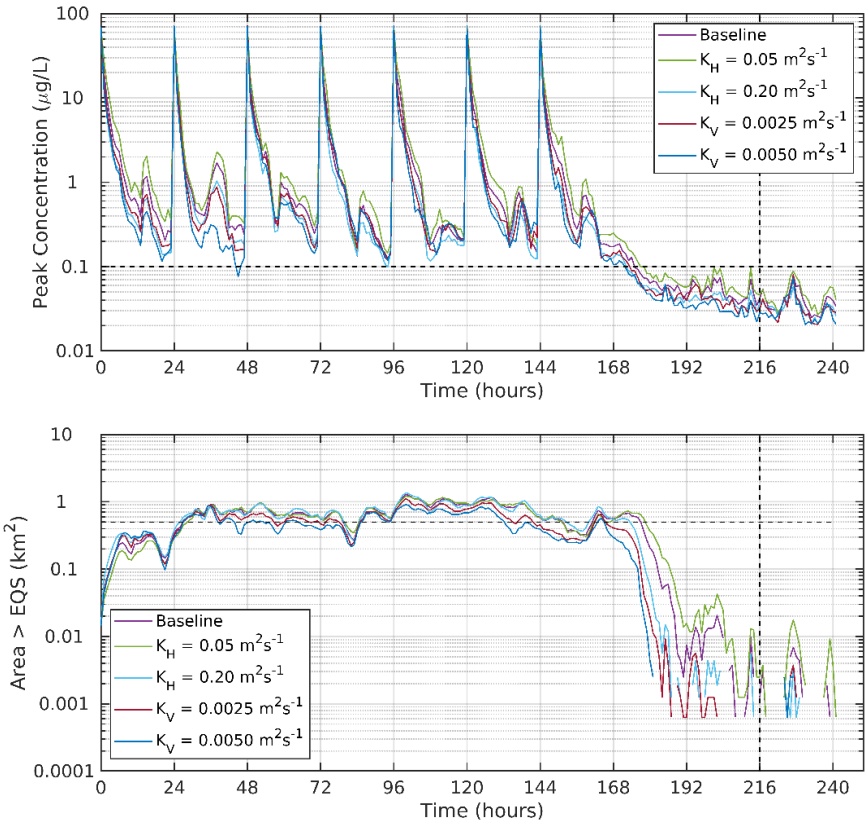

Figure 9. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tide with varying horizontal (K_H, m^2 s^{-1}) and vertical (K_V, m^2 s^{-1}) diffusion coefficients. The MAC and area limit 72 hours after the final treatment (Time = 216 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 simulations were 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 and in two cases there were very marginal and very brief exceedances of the MAC before the concentrations fell away rapidly again (Figure 10). The area-based EQS was comfortably achieved in all cases.

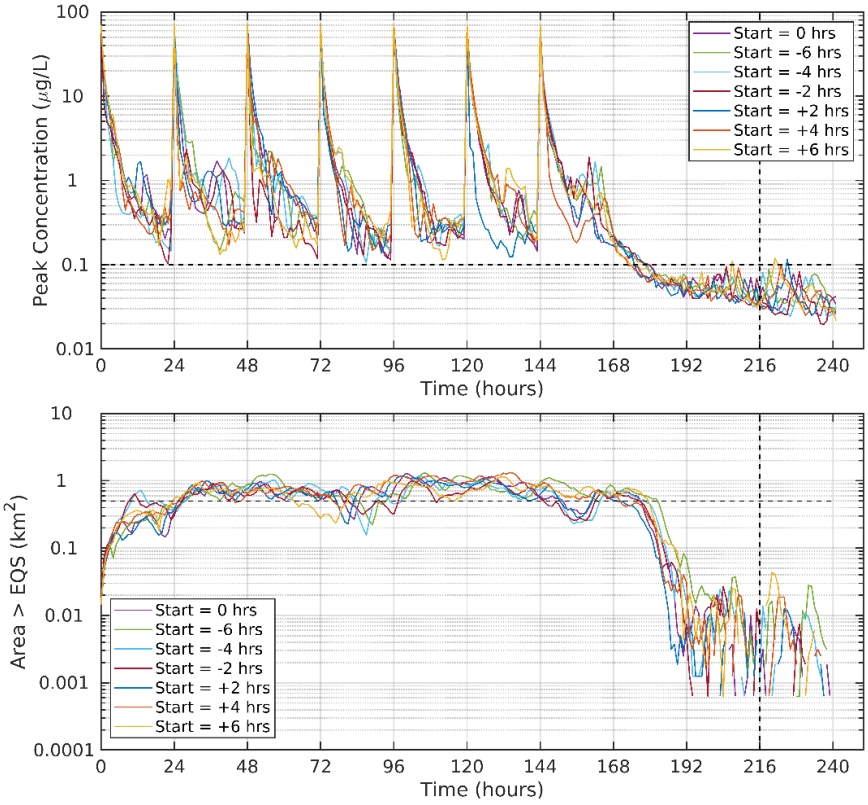

Figure 10. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km² are indicated by the horizontal dashed lines.

3.5 Dispersion during Spring Tides, May 2020

Dispersion simulations were carried out during modelled spring tides in May 2020 (Figure 5), repeating the simulations carried out for neap tides (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 1.021 kg of azamethiphos. For medicine half-lives of 5.6 days and 2.3 days, both the MAC and area EQS were achieved (Figure 11). Results with the long half-life of 8.9 days exhibited concentrations above the MAC for 5 hours after the 72-hour limit, but as noted above, this long half-life is not thought to accurately represent the breakdown timescale of azamethiphos in seawater; the Summary of Product Characteristics (SPC; Veterinary Medicines Directorate, 2020) specifies a half-life in seawater at 12°C of **less than** 5.6 days.

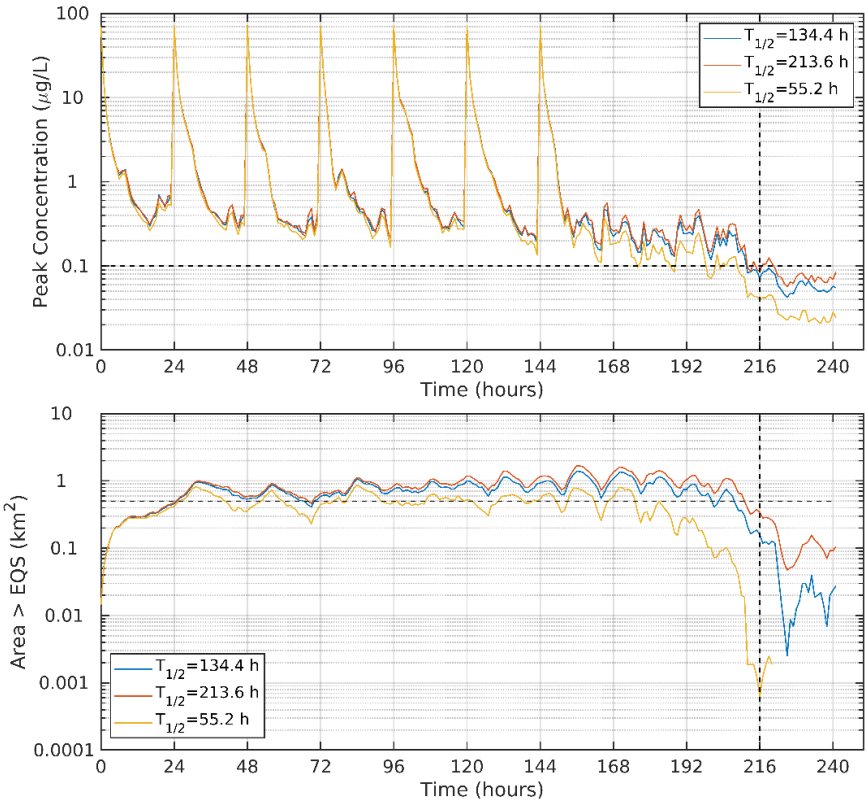

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fifth and sixth set of model runs (Table 4). The model was run during spring tide with varying medicine half-life ($T_{1/2}$). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km² are indicated by the horizontal dashed lines.

Results assessing the sensitivity of the spring tide predictions to the diffusion coefficients K_H and K_V are presented in Figure 12. All cases achieved EQS compliance, except for a brief breach of the MAC concentration with K_H = 0.05 m^2 s^{-1} (Figure 12); even at this very low horizontal diffusivity, the modelled breach only persisted for 2 – 3 hours before concentrations fall well below the MAC. In all cases, the area where concentrations exceeded 0.04 µg/L were well below the 0.5 km^2 limit after 216 hours (Figure 12).

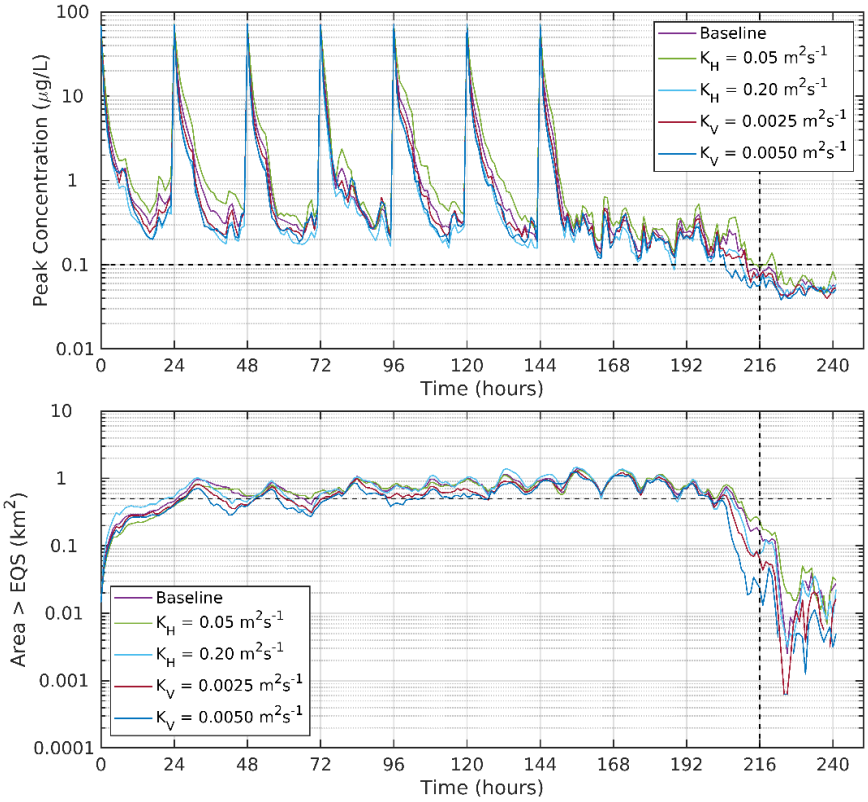

Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the seventh set of model runs (Table 4). The model was run during spring tide with varying horizontal (K_H, $m^2\ s^{-1}$) and vertical (K_V, $m^2\ s^{-1}$) diffusion coefficients. The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

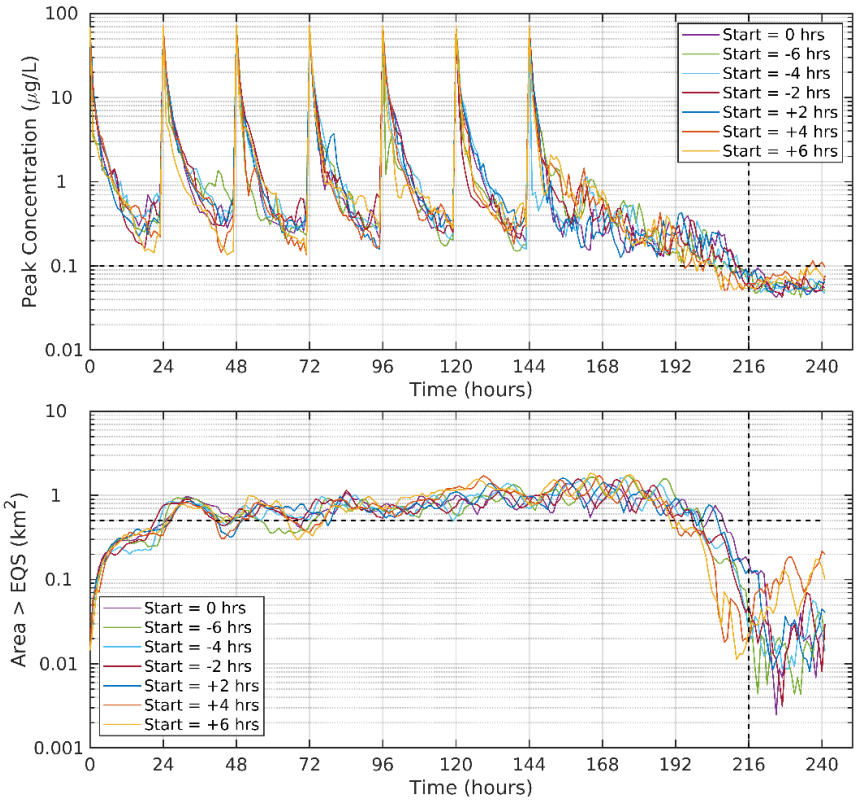

Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during spring tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.6 3-Hour EQS

The time series of the area where the 3-hour EQS of 250 ng L^{-1} was exceeded for each individual pen treatment at neap tide (first release on 9th May 2020) are shown in Figure 14. For each treatment, the area exceeding the EQS was less than the allowable mixing zone (0.12 km^2) after 3 hours. The peak concentration of 100 µg L^{-1} fell to less than 10 µg L^{-1} within the 3-hour period.

For spring tide releases (first release on 2nd May 2020), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 15). Similarly to the neap tide simulation, the peak concentrations fell by an order of magnitude within the three hours.

This demonstrates that the discharge of azamethiphos from the seven proposed 160m pens at the site should not breach the 3-hour Environmental Quality Standard.

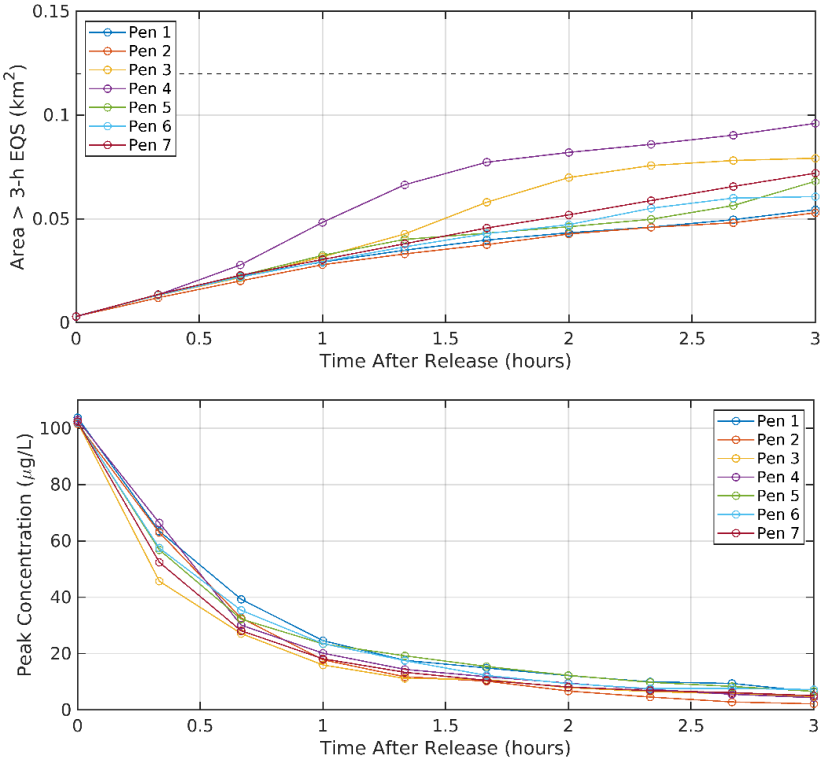

Figure 14. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

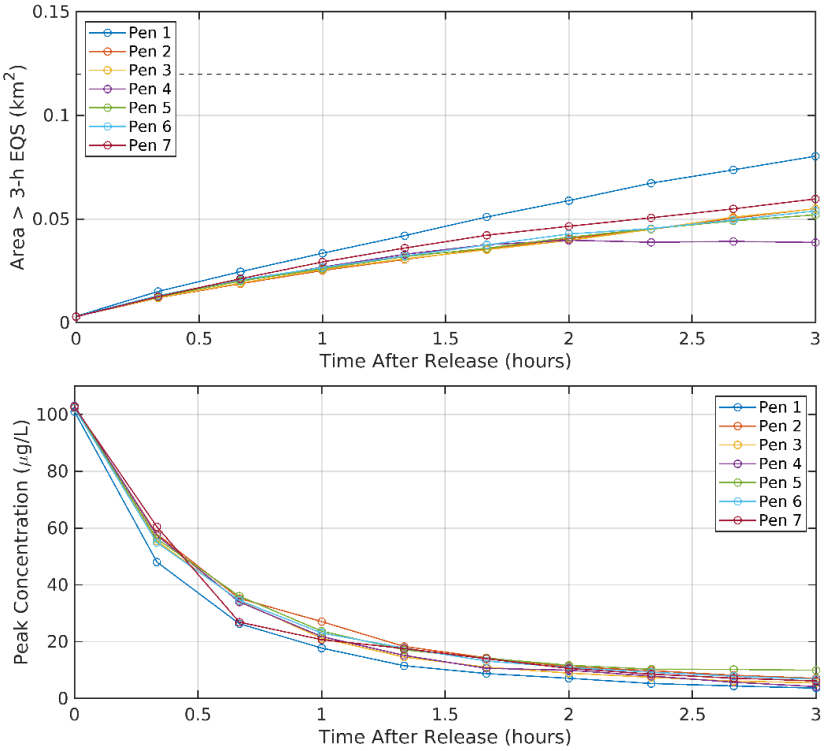

Figure 15. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

3.7 Cumulative Dispersion Simulations

The cumulative dispersion modelling included treatments at seven active local sites (Table 6). A total of 61 treatment discharges were made at neap and spring tides, with all sites completing treatment after 144 hours (Table 7). Standard parameter values were used (Table 8). The predicted mean concentrations of azamethiphos over the 72-hour period after the final treatment (145 – 216 hours) are shown in Figure 16. The modelled distributions of azamethiphos indicate that plumes from the four modelled Caol Mor sites (Sconser, Sconser Quarry, Maol Ban and Cairidh) interact to some degree. There is very limited interaction, if any, with the site at Scalpay, and none with the sites further north in Loch Portree.

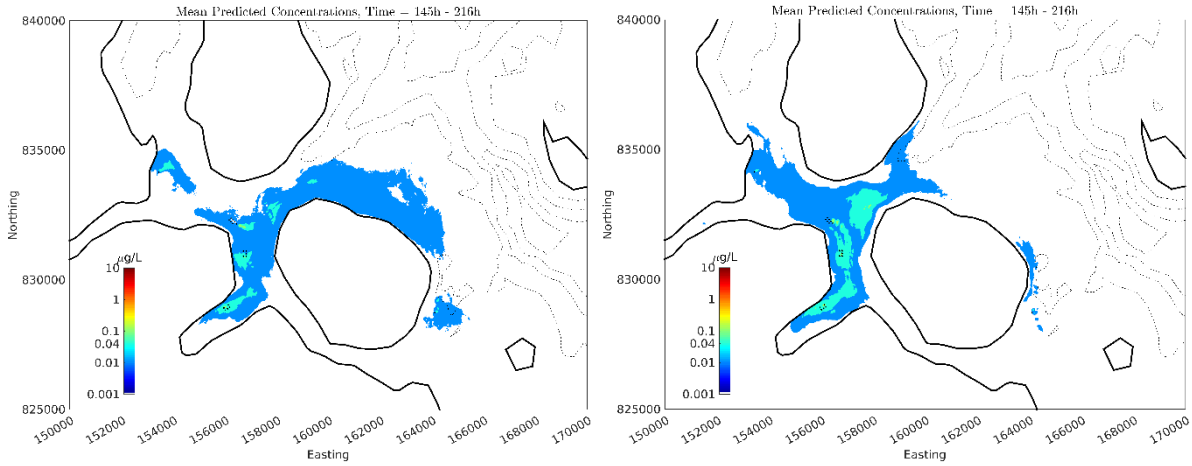

Figure 16: Mean predicted concentrations over the 72-hour period following the last treatment (Table 7) over neap tide (left) and spring tide (right).

Time series of peak concentration and area exceeding the EQS for each individual site included in the cumulative modelling are shown for neap tide (Figure 17) and spring tide (Figure 18). In the neap simulation (Figure 17), all sites complied with the EQS criteria, both the MAC and area-based conditions. In the spring tide simulation, the simulated discharge from Sconser exceeded the MAC and marginally breached the area-based EQS (Figure 18). However, it should be noted that Sconser is no longer an active site.

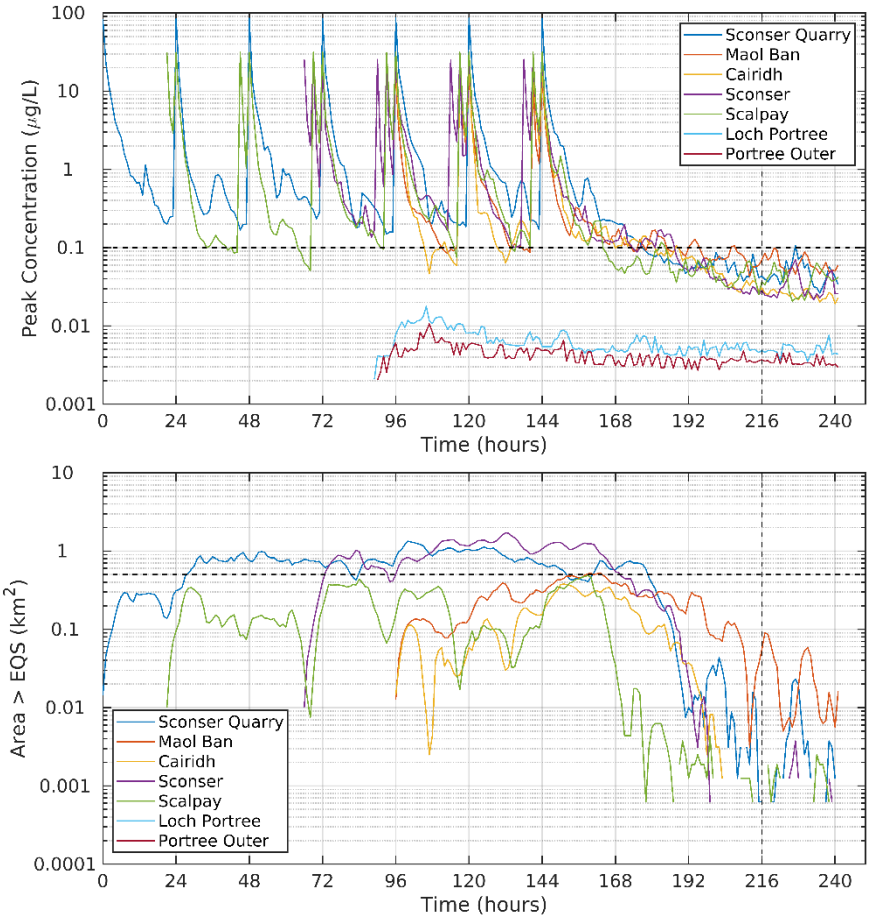

Figure 17: Time series of maximum concentration (top) and area exceeding the EQS (bottom) for each individual site included in the cumulative modelling over neap tide. The MAC and area limits 72 hours after the final treatment (Time = 216 hours) of 0.1 µg/L and 0.5 km² respectively are indicated by the horizontal dashed lines.

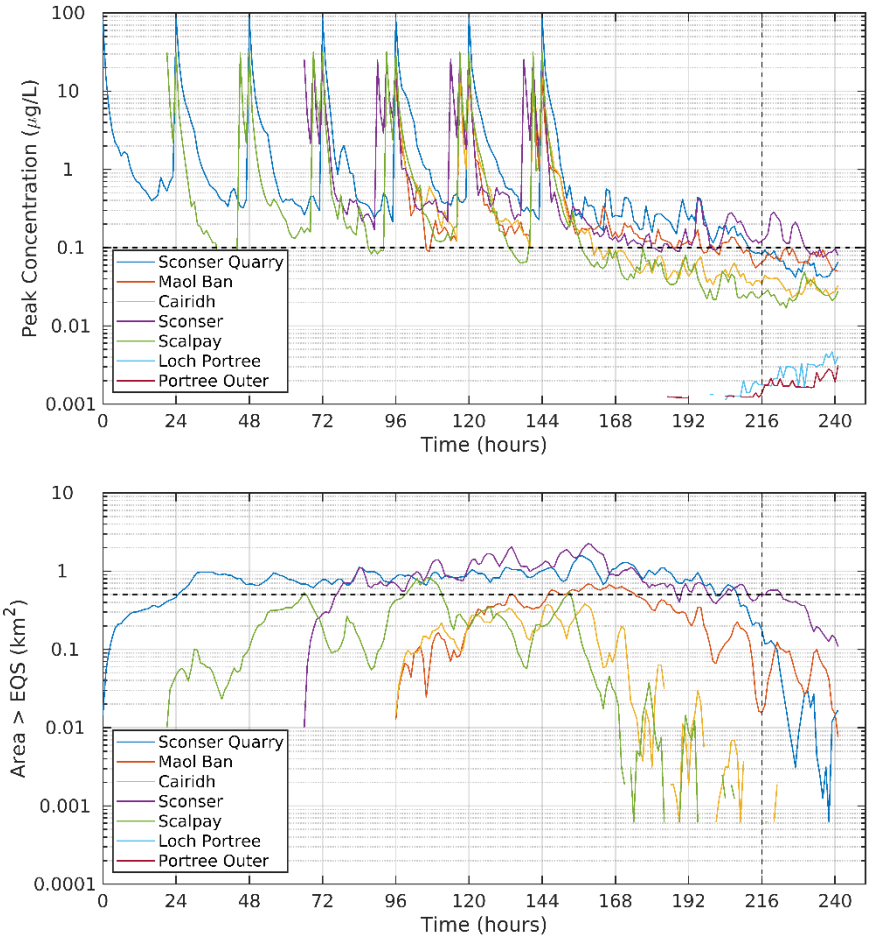

Figure 18: Time series of maximum concentration (top) and area exceeding the EQS (bottom) for each individual site included in the cumulative modelling over spring tide. The MAC and area limits 72 hours after the final treatment (Time = 216 hours) of 0.1 µg/L and 0.5 km² respectively are indicated by the horizontal dashed lines.

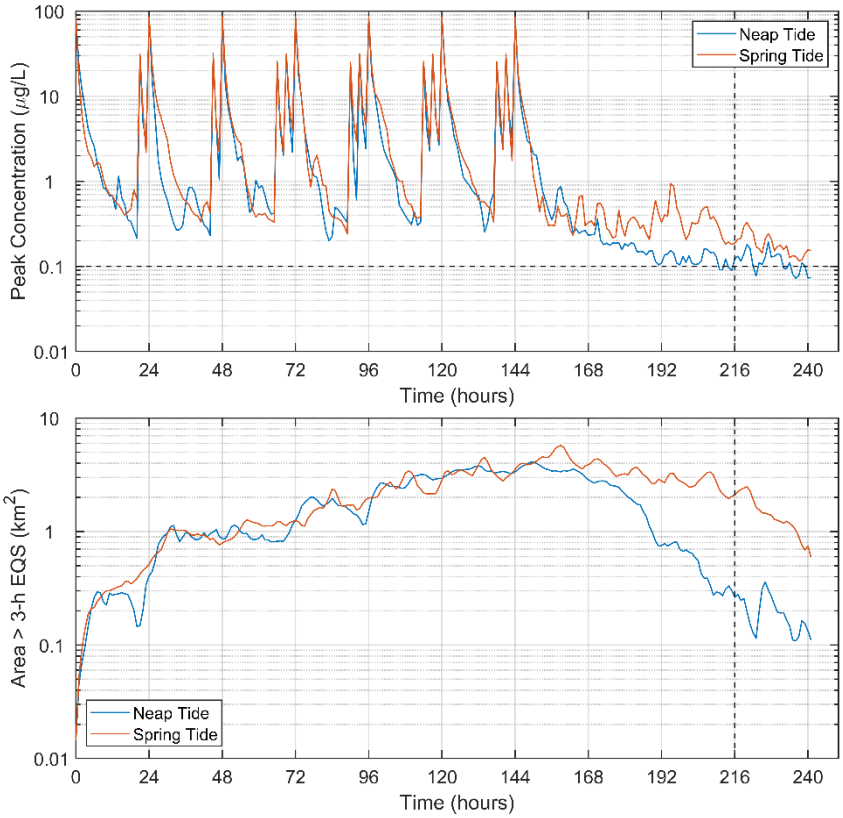

Figure 19. Time series of maximum concentration (top) and area exceeding a concentration of 0.04 µg/L (bottom) arising from all sites included in the cumulative modelling over neap and spring tides. The MAC limit 72 hours after the final treatment (Time = 216 hours) of 0.1 µg/L is indicated by the horizontal dashed line.

4 SUMMARY AND CONCLUSIONS

A total of 28 dispersion simulations have been performed to assess whether bath treatments at Sconser Quarry salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1.021 kg of azamethiphos for treatment, resulting in a total discharge over 7 days of 7.147 kg. Simulations were performed separately for neap and spring tides, and the sensitivity of the results to key model parameters was tested. Results are summarised in Table 9.

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 1.021 kg, should consistently comply with the EQS. Using standard, reasonable parameter values, the peak concentration after 216 hours (72 hours after the final treatment) was consistently 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. Sensitivity testing showed that, in a small number of cases, with relatively extreme parameter values (e.g. $T_{1/2}$ = 8.9 days; K_H = 0.05 m^2 s^{-1}), very minor and very brief breaches of the MAC condition were predicted. It is believed that, in reality, such breaches are extremely unlikely to occur due to the unrepresentative nature of the parameter values used in these

cases. Further, the modelled half-life of 5.6 days is believed to be a relatively conservative value for the actual half-life of azamethiphos in seawater.

Table 9. Summary of Results

Site Details	
Site Name:	Sconser Quarry
Site Location:	Caol Mor
Peak Biomass (T):	2,500
Pen Details	
Number of Pens:	7
Pen Dimensions:	160m circumference
Working Depth (m):	16
Pen Group Configuration:	2 x 3 + 1
Azamethiphos	
Recommended 3hr Consent (kg):	1.021
Recommended 24hr Consent (kg):	1.021

Cumulative dispersion modelling undertaken for seven sites in the Caol Mor region demonstrated that individually all sites except Sconser passed the MAC and area-based EQS conditions. This includes the three active Caol Mor sites (Sconser Quarry, Maol Ban and Cairidh) for quantities of azamethiphos that are currently being proposed. The site at Sconser is no longer being operated. No interaction was evident between the Caol Mor sites and sites in the Sound of Rassay.

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 7.

5 REFERENCES

Dale. A., Allen. C., Venables. E., Beaton. J. & Aleynik. D. (2020). Dye tracer dispersion studies in support of bath treatment models for fish farms (2020). A study commissioned by the Scottish Aquaculture Research Forum (SARF). http://www.sarf.org.uk/SARFSP012.pdf

Edwards, A., 2015. A note on dispersion in West Scottish coastal waters. A Report for Benchmark Animal Health. September 2015, 55pp.

European Centre for Medium-Range Weather Forecasts (ECMWF) 2021, ERA5 Dataset https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

Gillibrand, P.A., 2021. Unptrack User Guide. Mowi Scotland Ltd., February 2021, 31pp.

Gillibrand, P.A., B. Siemering, P.I. Miller and K. Davidson, 2016a. Individual-Based Modelling of the Development and Transport of a Karenia mikimotoi Bloom on the North-West European Continental Shelf. Harmful Algae, DOI: 10.1016/j.hal.2015.11.011

Gillibrand, P.A., Walters, R.A., and McIlvenny, J., 2016b. Numerical simulations of the effects of a tidal turbine array on near-bed velocity and local bed shear stress. *Energies*, vol 9, no. 10, pp. 852. DOI: 10.3390/en9100852

Gillibrand, P.A. and K.J. Willis, 2007. Dispersal of Sea Lice Larvae from Salmon Farms: A Model Study of the Influence of Environmental Conditions and Larval Behaviour. Aquatic Biology, 1, 73-75.

Lewis, R. 1997. Dispersion in Estuaries and Coastal Waters. John Wiley & Sons, 332 pp.

McIlvenny, J. , Tamsett, D., Gillibrand, P.A. and Goddijn-Murphy, L., 2016. Sediment Dynamics in a Tidally Energetic Channel: The Inner Sound, Northern Scotland. Journal of Marine Science and Engineering, 4, 31; doi:10.3390/jmse4020031

Mowi Scotland Ltd, 2022. Caol Mor Hydrodynamic Model Description, January 2022, 22 pp.

Marine Scotland, 2016. Scottish Shelf Model. Part 4: East Coast of Lewis and Harris Sub-Domain. Available at https://www.gov.scot/publications/scottish-shelf-model-part-4-east-coast-lewis-harris-sub/pages/4/

Okubo, A., 1971. Oceanic diffusion diagrams. Deep-Sea Research, 18, 789 – 802.

SEPA, 2019. Aquaculture Modelling. Regulatory modelling guidance for the aquaculture sector. Scottish Environment Protection Agency, Air & Marine Modelling Unit, June 2019, 68pp.

SEPA, 2021. Interim Marine Modelling Guidance For Aquaculture Applications. Scottish Environment Protection Agency, December 2021. 5 pp.

UKHO 2022, https://www.admiralty.co.uk/digital-services/data-solutions/admiralty-marine-data-portal

Veterinary Medicines Directorate, 2020. Salmosan Vet Summary of Product Characteristics. Available at https://www.vmd.defra.gov.uk/productinformationdatabase/files/SPC_Documents/SPC_720682.PDF

Walters, R.A.; Casulli, V., 1998. A robust, finite element model for hydrostatic surface water flows. Comm. Num. Methods Eng., 14, 931–940.

Willis, K.J, Gillibrand, P.A., Cromey, C.J. and Black, K.D., 2005. Sea lice treatments on salmon farms have no adverse effect on zooplankton communities: A case study. *Marine Pollution Bulletin*, 50, 806 – 816.