Marine Aquaculture Site Loch Hourn

Appendix 4. Azamethiphos Dispersion Modelling

Mowi Scotland Limited
November 2021

[redacted]

Azamethiphos Dispersion Modelling

CREAG AN SAGAIRT, LOCH HOURN

Mowi Scotland Limited

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[redacted]

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Loch Hourn salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1.23 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 9.84 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 1.23 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:		Creag an T'Sagairt	
Site location:		Loch Hourn	
Peak biomass (T):		3,100	
PEN DETAILS			
Number of pens:		8	
Pen dimensions:		160m Circumference	
Working Depth (m):		20	
Pen group configuration:		1 x 8, 100m matrix	
HYDROGRAPHIC SUMMARY		**ID246**	**ID275**
Surface Currents	**Hourn**	**Sep-Nov 2018**	**Apr-Jul 2019**
	Mean Speed (m/s)	0.066	0.042
	Residual Speed (m/s)	0.040	0.018
	Residual Direction (°G)	330	277
	Tidal Amplitude Parallel (m/s)	0.091	0.066
	Tidal Amplitude Normal (m/s)	0.026	0.025
	Major Axis (°G)	330	295
BATH TREATMENTS			
Recommended consent mass - 3hr Azamethiphos (kg)		1.23	
Recommended consent mass - 24hr Azamethiphos (kg)		1.23	

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 in Loch Hourn (Figure 1). The report presents results from coupled hydrodynamic and particle tracking modelling to describe the dispersion of bath treatments to determine EQS-compliant quantities for the current site biomass and equipment. The modelling procedure follows as far as possible guidance presented by SEPA in June 2019 (SEPA, 2019).

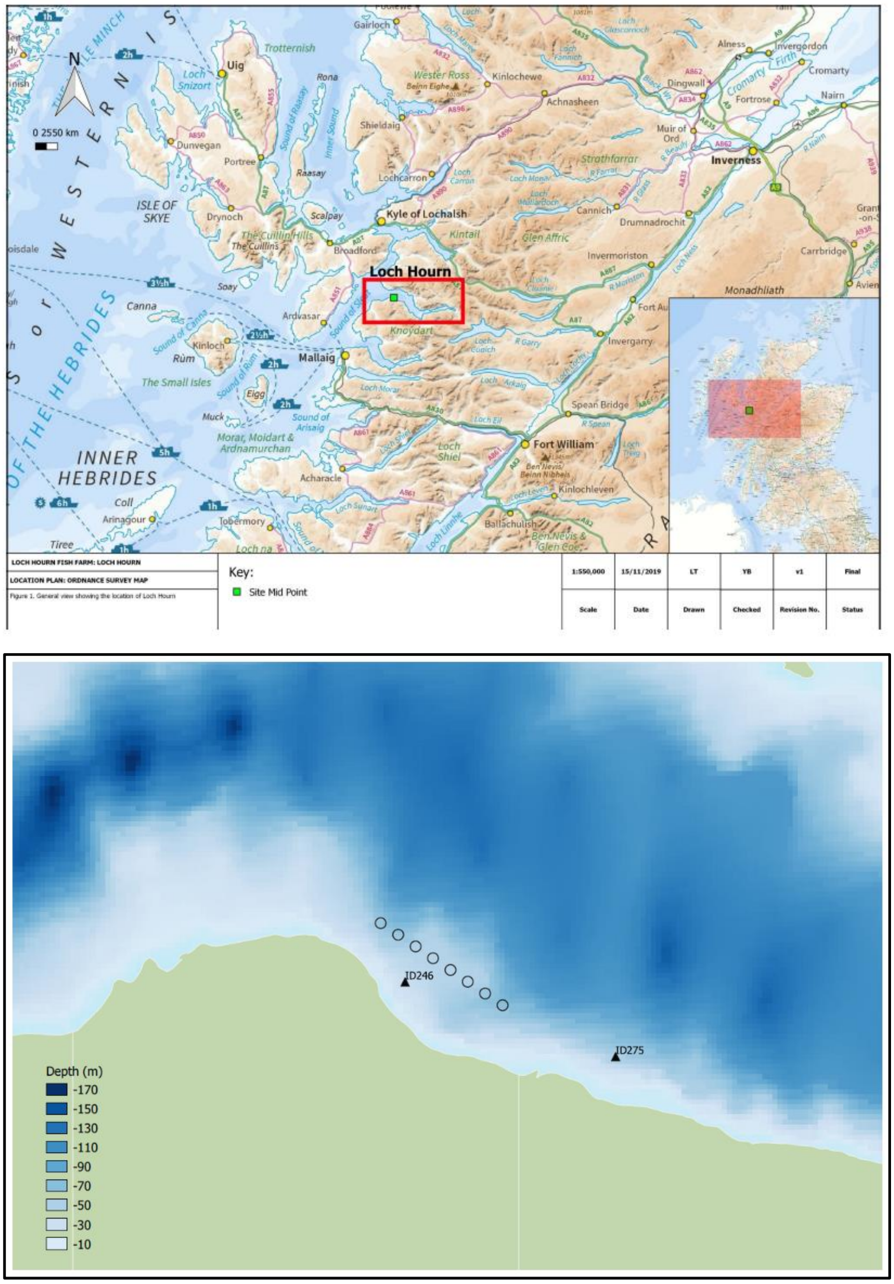

Figure 1. Location of Loch Hourn salmon farm (top) and the location of the ADCP deployments in 2018 and 2019 (▲) relative to the proposed pen positions (**o**).

1.1 Site Details

The site is situated off the South Shore of Loch Hourn (Figure 1). Details of the site are provided in Table 2. The receiving water is defined as a sea loch.

Table 2. Project Information

SITE DETAILS		
Site Name:		Creag an T'Sagairt
Site location:		Loch Hourn
Peak biomass (T):		3,100
Proposed feed load (T/yr):		7,920.5
Proposed treatment use:		Azamethiphos
PEN DETAILS		
Group location:		NG 80170 09792
Number of pens:		8
Pen dimensions:		160m circumference
Grid matrix (m)		100
Working Depth (m):		20
Pen group configuration:		1 x 8
Pen group orientation (°G):		125.0
Pen group distance to shore (km):		0.171
Water depth at site (m):		45 – 60
HYDROGRAPHIC DATA		
	ID246	**ID275**
Current meter position:	179910, 809766	180912, 809410
Depth at deployment position (m):	34.61	60.42
Surface bin centre height above bed (m):	27.72	50.71
Middle bin centre height above bed (m):	16.72	42.71
Bottom bin centre height above bed (m):	3.72	3.71
Duration of record (days):	55	64
Start of record:	11-Sep-2018	30-Apr-2019
End of record:	05-Nov-2018	04-Jul-2019
Current meter averaging interval (min):	20	20
Magnetic correction to grid North:	-0.30605	-0.20029
BATH TREATMENTS		
Recommended consent mass - 3hr Azamethiphos (kg)		1.23
Recommended consent mass - 24hr Azamethiphos (kg)		1.23

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, Loch Hourn Hydrodynamic Model Description, 2021), 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., 2016).

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., 2016) 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 Loch Hourn to illustrate the quantities of medicine that disperse safely in the environment.

2.1 Model Domain and Boundary Conditions

The unstructured mesh used in the model was adapted from the East Coast of Lewis and Harris (ECLH) sub-model mesh of the Scottish Shelf Model (SSM; MS, 2016). The model resolution was enhanced in the Loch Hourn area, particularly around the Mowi site. The domain and mesh is shown in Figure 2, with the area around Loch Hourn shown in Figure 3.

The mesh was not refined down to 25m specifically in the area of the pens, since dispersion of topical medicines is not a localised process, unlike particulate deposition, and takes place over a much wider area. However, the mesh is relatively highly resolved in the Loch Hourn area (Figure 3) and is completely adequate for modelling dispersion of solutes. The spatial resolution of the model varied from 25m in some inshore waters to 5 km along the open boundary. In total, the model consisted of 42,286 nodes and 79,245 triangular elements.

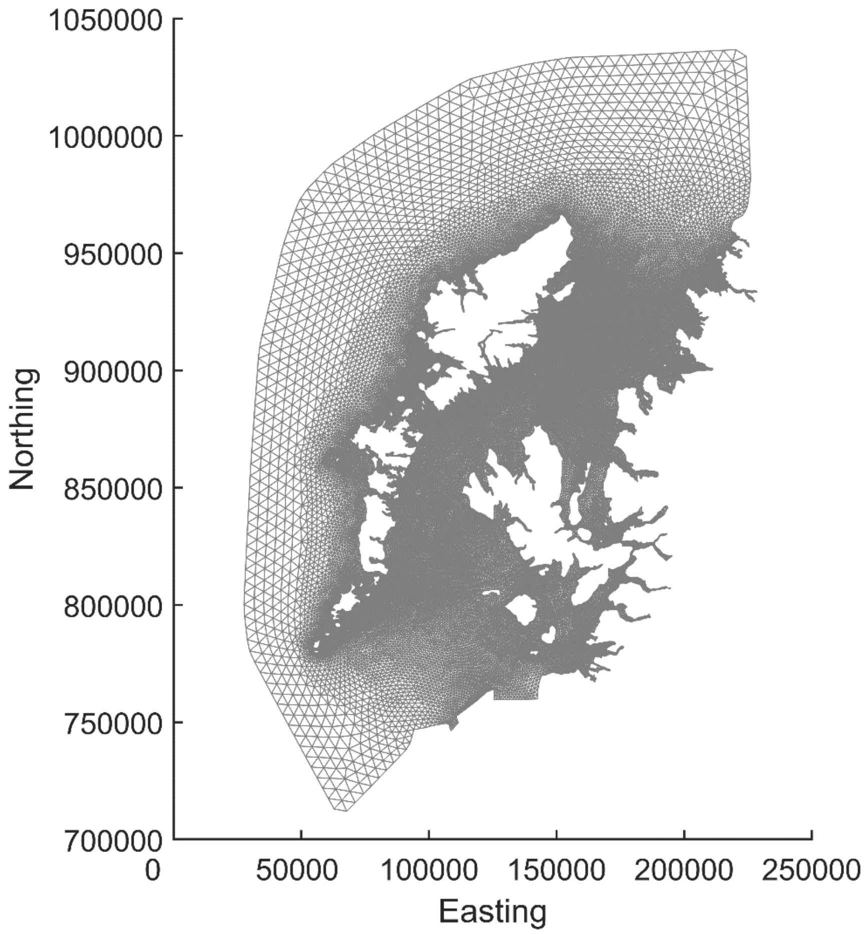

Figure 2. The modified ECLH domain and mesh used in the Loch Hourn modelling.

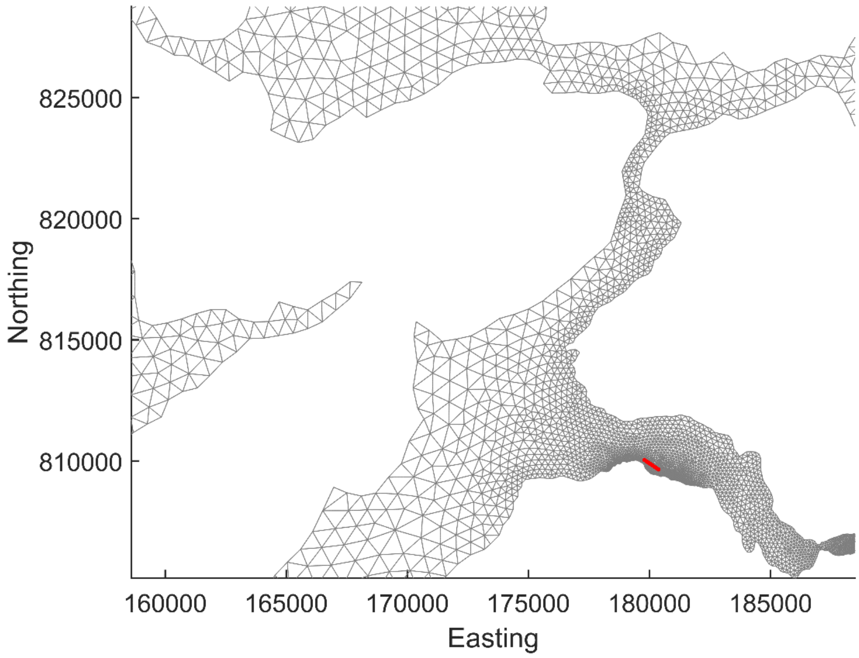

Figure 3. The model mesh in the area around the Loch Hourn site. The pen locations are indicated (○).

Bathymetry from the original model (Figure 4) was supplemented by Admiralty bathymetry data and a local depth survey. Water depths from this combination of sources were smoothly interpolated onto the modified model node locations (Figure 5).

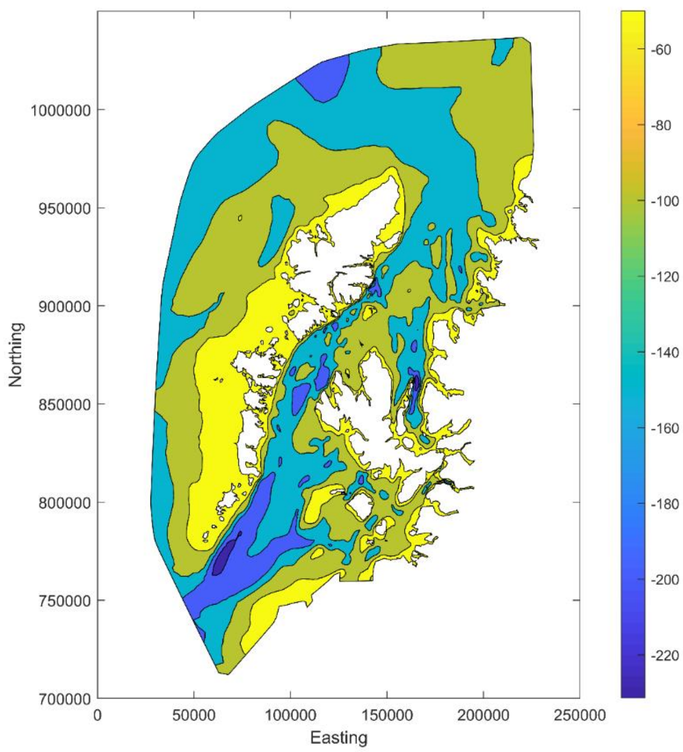

Figure 4. Bathymetry, H (m), in the ECLH domain.

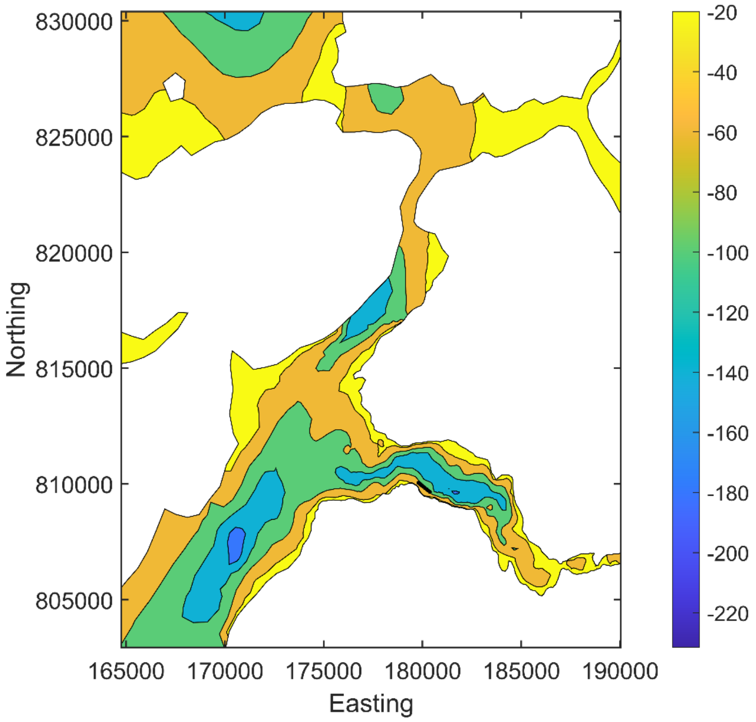

Figure 5. Localised bathymetry (m) around Loch Hourn in the ECLH domain. The pen locations are marked (•).

The model was forced along its open boundary by eight tidal constituents (O_1, K_1, Q_1, P_1, M_2, S_2, N_2, K_2), amplitudes and phase of which were obtained from the full SSM. Spatially- and temporally-varying wind speed and direction data were taken from the ERA5 global reanalysis dataset for the required simulation periods (ECMWF, 2021).

Stratification is relatively weak in this location, with Loch Hourn having one of the lowest freshwater/tidal flow ratios of Scottish sea lochs, ranked 86 out of 109 with an estimated salinity reduction of 0.2 PSU (Edwards and Sharples, 1986). As such, the model was run in 2D vertically-averaged mode.

Full details of the calibration and validation of the hydrodynamic model are given in the Hydrodynamic Model Description (Mowi Scotland Ltd, Loch Hourn Hydrodynamic Model Description, 2021).

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 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 120 µg/L, with a total mass of 9.84 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.* 980,000 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. This grid covered the area shown in Figure 3.

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 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 2019 (Figure 6). Further sets of simulations were performed at neap tides from 2018 to confirm the adequacy of dispersion during the weakest tides (Figure 7).

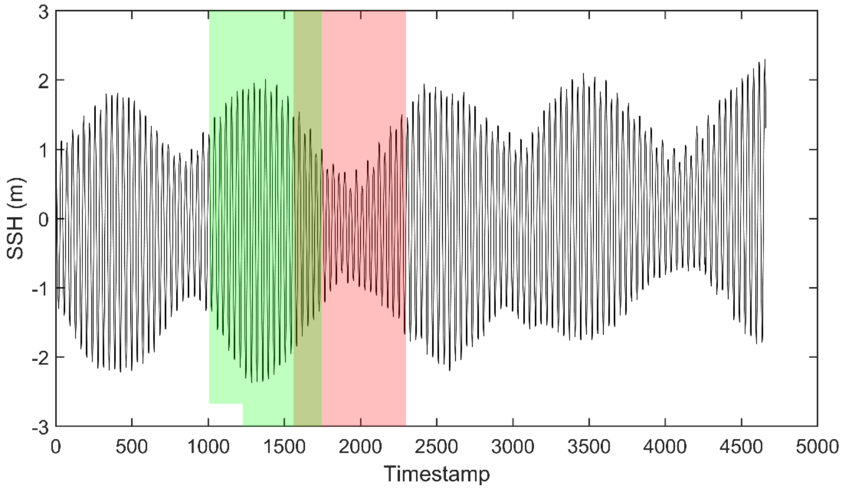

Figure 6. Sea surface height (SSH) at Loch Hourn from 30th April – 4th July 2019 (ID275). Dispersion simulations were performed over periods of spring tides (Green, start day 14th May 2019) and neap tides (red, start day 22nd May 2019).

2.3 Medicine Dispersion Simulations

The pens 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 6 and Figure 7.

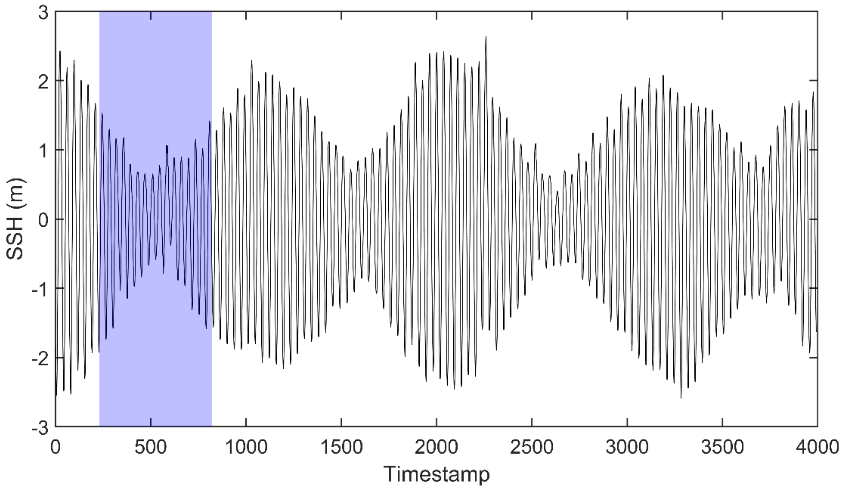

Figure 7. Sea surface height (SSH) at Loch Hourn from 11th September 2018 – 5th November 2018 (ID246). Dispersion simulations were performed over periods of neap tides (blue, start day 14th September 2018).

The simulations performed are listed in Table 4. All simulations used the release schedule and quantities outlined in Table 3. In Runs 2 – 7, 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 6 and Figure 7.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (kg)	Release Time (hr)
1	180043	809879	5.0	1.23	0
2	179960	809935	5.0	1.23	24
3	179877	809991	5.0	1.23	48
4	179794	810046	5.0	1.23	72
5	180374	809655	5.0	1.23	96
6	180291	809711	5.0	1.23	120
7	180208	809767	5.0	1.23	144
8	180126	809823	5.0	1.23	168

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

Set	Run No.	$T_{1/2}$ (h)	K_H	K_V	Start Time
Neap Tides, Start day = 22 (22nd May 2019, ID275)					
Baseline	1	134.4	0.143	0.001	12:00
1	2	134.4	0.143	0.001	12:00 -6h
	3	134.4	0.143	0.001	12:00 -4h
	4	134.4	0.143	0.001	12:00 -2h
	5	134.4	0.143	0.001	12:00 +2h
	6	134.4	0.143	0.001	12:00 +4h
	7	134.4	0.143	0.001	12:00 +6h
2	8	213.6	0.143	0.001	12:00
	9	55.2	0.143	0.001	12:00
3	10	134.4	0.1	0.001	12:00
	11	134.4	0.2	0.001	12:00
4	12	134.4	0.143	0.0025	12:00
	13	134.4	0.143	0.005	12:00
Spring Tides, Start day = 14 (14th May 2019, ID275)					
5	14	134.4	0.143	0.001	12:00
	15	213.6	0.143	0.001	12:00
	16	55.2	0.143	0.001	12:00
6	17	134.4	0.1	0.001	12:00
	18	134.4	0.2	0.001	12:00
7	19	134.4	0.143	0.0025	12:00
	20	134.4	0.143	0.005	12:00
Neap Tides, Start day = 3 (14th Sept 2018, ID246)					
8	21	134.4	0.143	0.001	12:00
	22	213.6	0.143	0.001	12:00
	23	55.2	0.143	0.001	12:00
9	24	134.4	0.1	0.001	12:00
	25	134.4	0.2	0.001	12:00
10	26	134.4	0.143	0.0025	12:00
	27	134.4	0.143	0.005	12:00

2.4 Diffusion Coefficients

Selection of the horizontal diffusion parameter, K_H, was guided by dye releases conducted in the Loch Hourn region by Anderson Marine Surveys Ltd on 12th April 2017. 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 8 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 0.143 $m^2 s^{-1}$. There is considerable scatter in the data (Figure 8), arising from the difficulty of tracking dye in the marine environment which renders individual values highly uncertain.

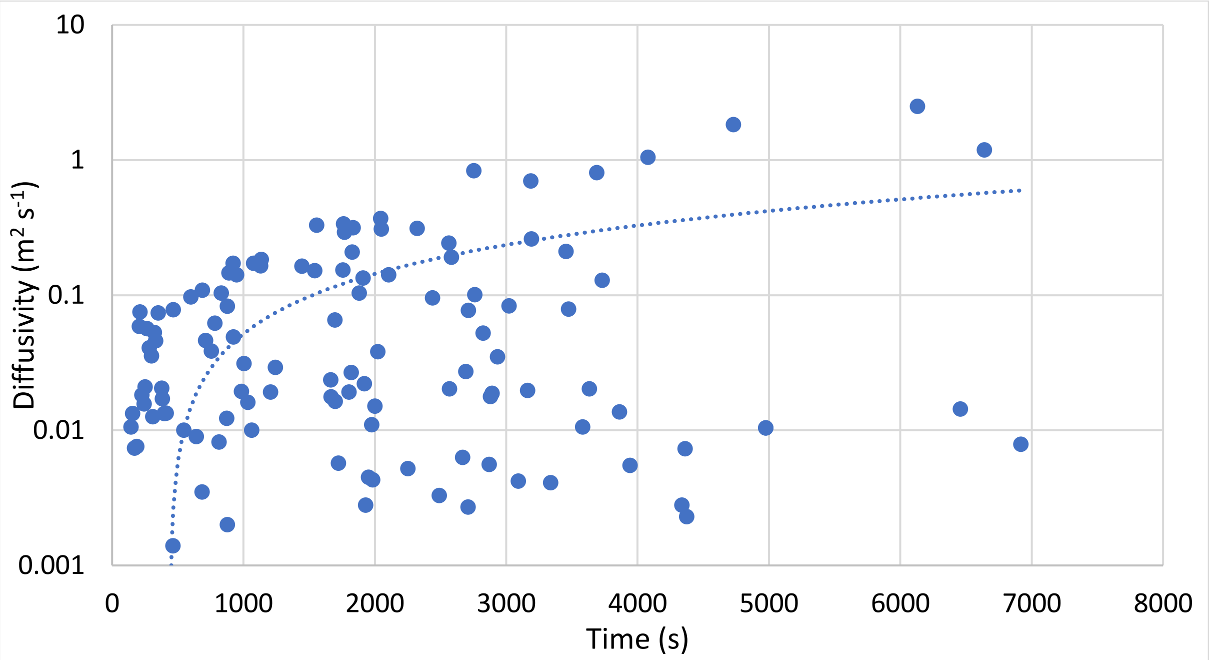

Figure 8. Estimated horizontal diffusivity ($m^2 s^{-1}$) from dye release experiments at Loch Hourn on 12th April 2017. The mean diffusivity was 0.143 $m^2 s^{-1}$.

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:

$$C_{max} = \frac{M}{4\pi HKt} \tag{1}$$

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. 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 9. 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.

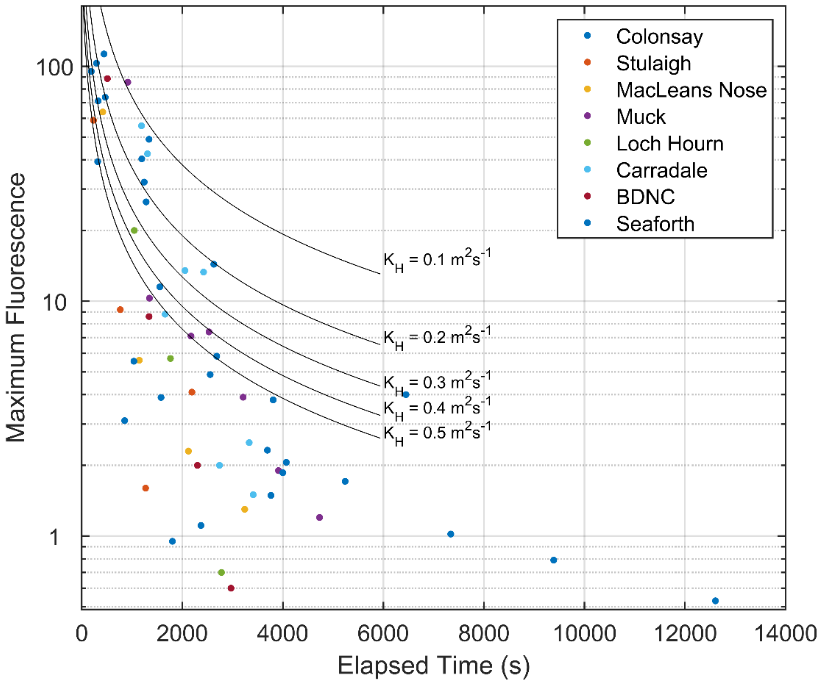

Figure 9. Maximum fluorescence measured following dye releases at a number of Mowi sites in Scotland. The data points from Loch Hourn are green. The black lines indicate the rate at which the maximum concentration would fall at different horizontal diffusivities.

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 = 0.143 m^2 s^{-1}, the mean horizontal diffusion given from the dye releases at Loch Hourn. However, the sensitivity of the model to K_H was explored.

3 RESULTS

3.1 Dispersion During Neap Tides, May 2019

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 120 µg/L, resulted in a treatment mass per pen of azamethiphos of 1.23 kg, a daily (24-h) release of 1.23 kg and a total treatment release of 9.84 kg over 168 hours. The dispersion of the medicine during and following treatment from Run001 is illustrated in Figure 10. 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 120 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 120 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 120 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 northwards through the Sound of Sleat. 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. A remnant of medicine remains in Loch Hourn but at concentrations below the MAC.

The time series of maximum concentration from the simulation is shown in Figure 11. The 8 peaks in concentration of ~120 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 11). 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 1.3 km^2 during treatment on Day 4, 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 10 and Figure 11).

These results indicate that, with a horizontal diffusion coefficient of 0.143 m^2 s^{-1}, given from the dye release study, 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.

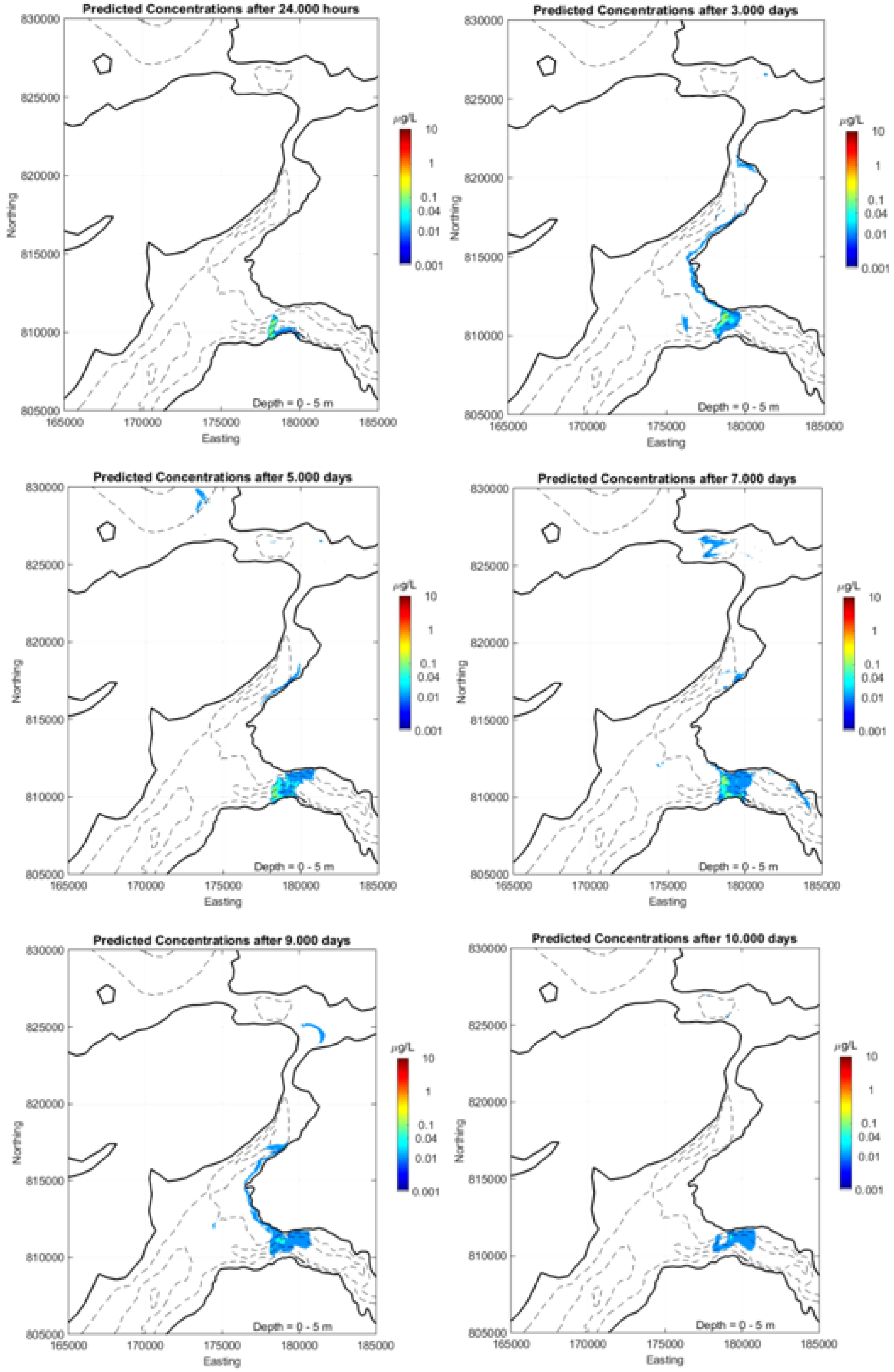

Figure 10. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 72 hours (top right), 120 hours (middle left), 168 hours (middle right), 216 hours (bottom left) and 240 hours (bottom right).

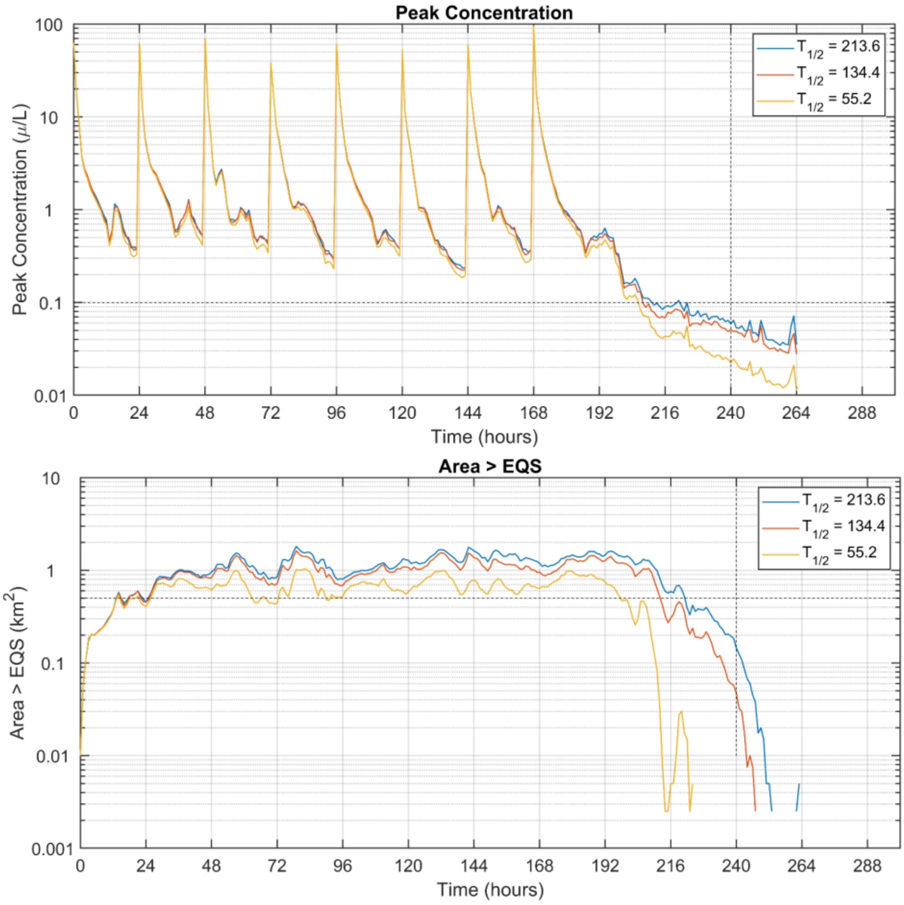

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tide with varying medicine half-life ($T_{1/2}$). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L and 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 11). The area where the EQS of 0.04 µg/L is exceeded peaked at about 1.9 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 11). 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 = 0.143 m^2 s^{-1}, which was the resulting diffusion coefficient of the dye release study. Simulations were also performed with lower and higher values of K_H, specifically K_H = 0.1 m^2 s^{-1} and K_H = 0.2 m^2 s^{-1} (Table 4).

The time series of maximum concentration and area exceeding the EQS are shown in Figure 12. The time series confirm that the MAC was not exceeded after 240 hours (72 hours after the final treatment) with either the lower or higher value of K_H. 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 13). 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.

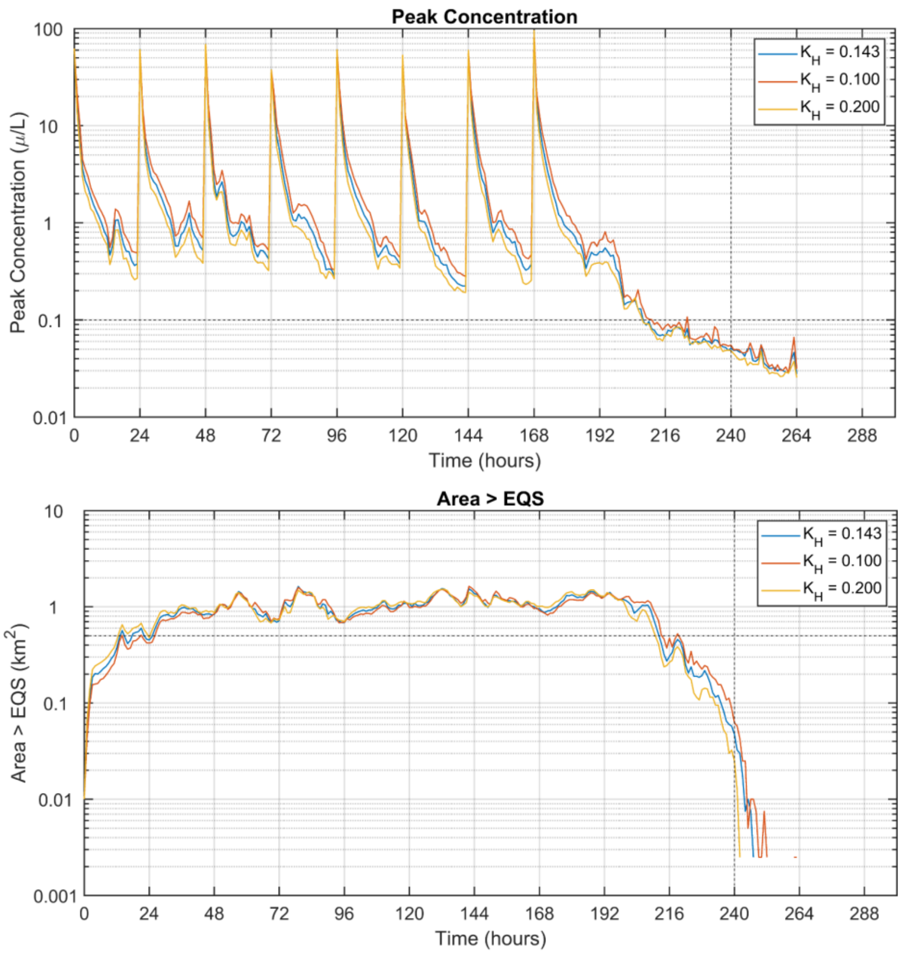

Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient K_H (m^2 s^{-1}). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

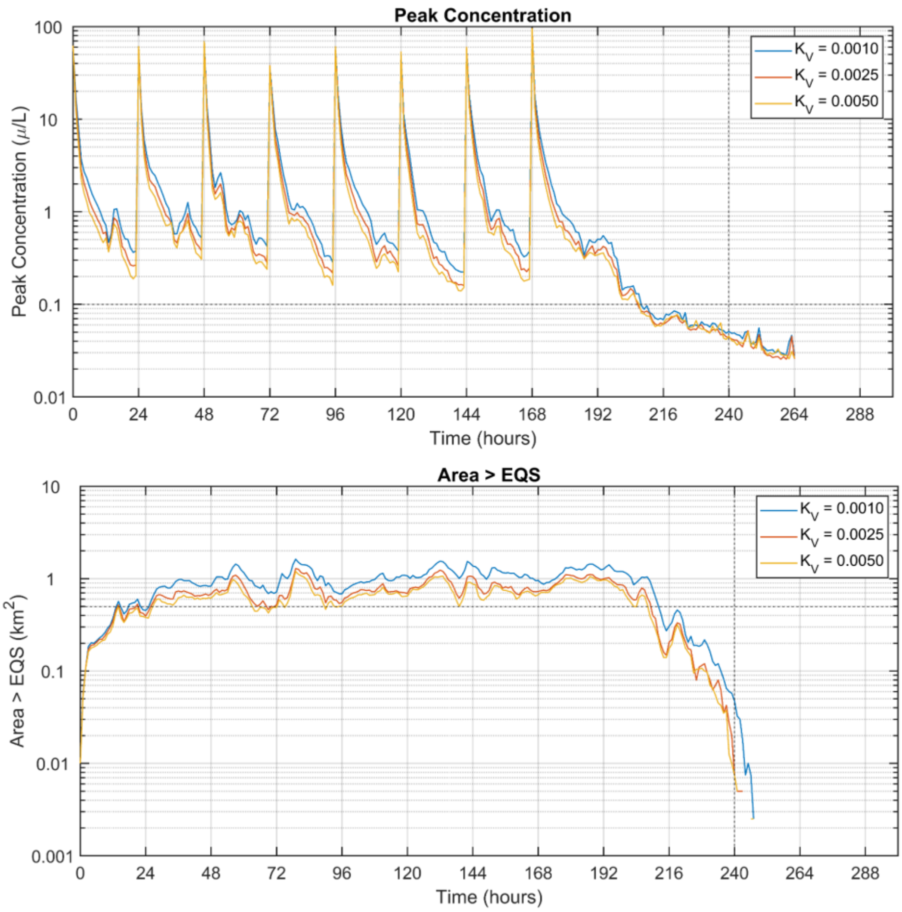

Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient K_V ($m^2 s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 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 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 little variability (Figure 14), However, in no case was the MAC exceeded after 240 hours.

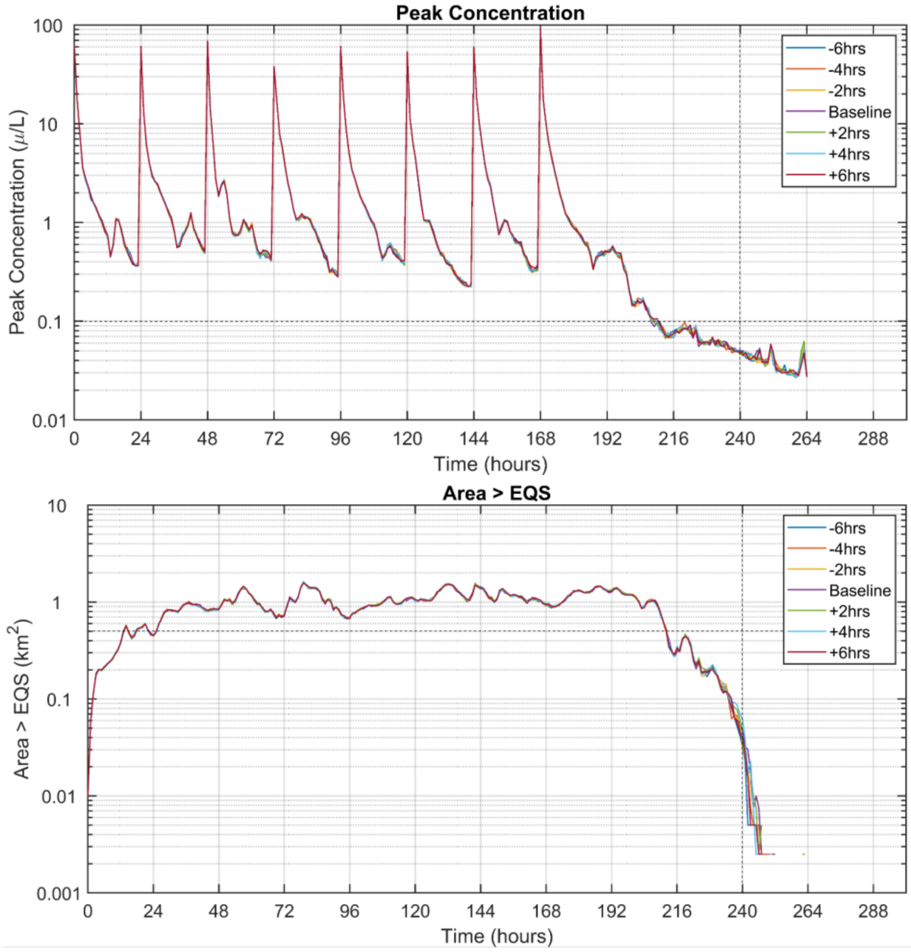

Figure 14. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 12 h). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.5 Dispersion during Spring Tides, May 2019

Dispersion simulations were carried out during modelled spring tides in May 2019 (Figure 6), 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 1.23 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 15). Dispersion at spring tides is significantly greater than at the very small tidal range during the neap tide simulated in May 2019.

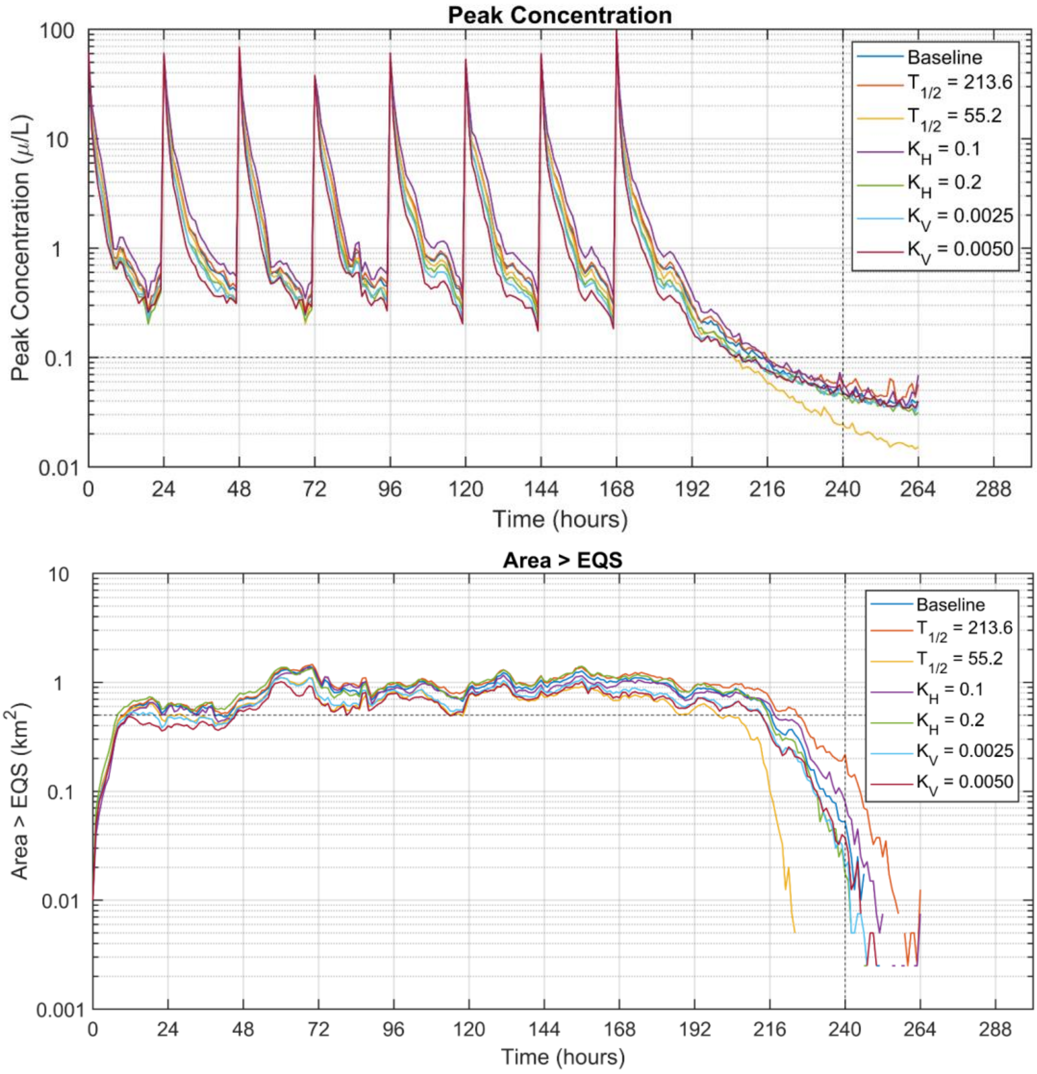

Figure 15. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient K_H ($m^2\ s^{-2}$) 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.

Given the comfortable compliance with the MAC and EQS at spring tides, simulations investigating the effects of release times were not performed.

3.6 Dispersion During Neap Tides, September 2016

A further set of dispersion simulations during modelled neap tides in September 2018 (Figure 7), repeating the main set carried out for neap tides in May 2019 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 1.23 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.

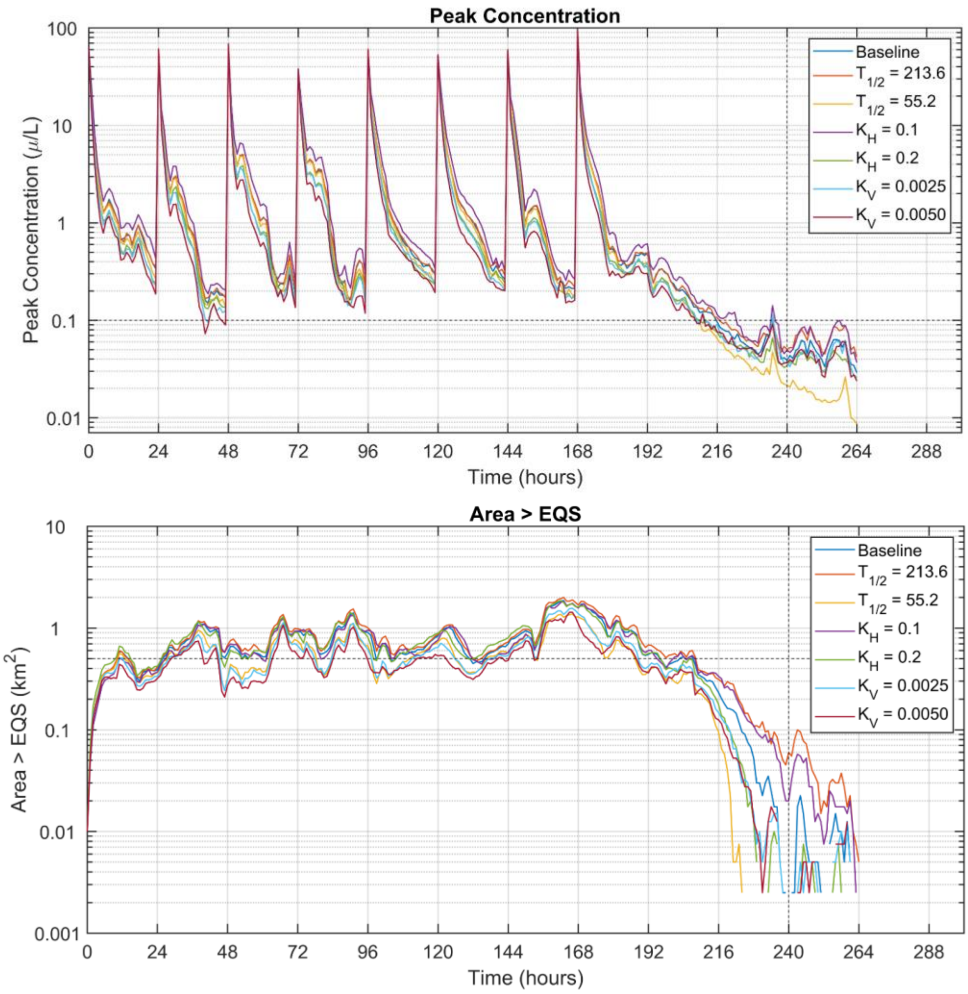

Figure 16. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, nineth and tenth set of model runs (Table 4). The model was run at neap tides in September 2018 with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient 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.

4 CUMULATIVE MODELLING

As well as sensitivity analysis, cumulative bath modelling was also undertaken for Loch Hourn and several near-by sites to check for any interaction between treatments. Three sites situated near the Loch Hourn site, at Arnisdale, Loch na Beiste and Camas na Gall, were not included in the cumulative modelling since these sites do not have a consent to discharge azamethiphos. Table 5 shows details of the additional sites used in the cumulative model runs alongside Loch Hourn.

Table 5. Details of additional sites included in cumulative modelling

	Ardintoul	Duich	Earnsaig (Nevis A)	Sron (Loch Alsh)
Company:	Mowi	Mowi	Scottish Sea Farms	Mowi
Site location:	NG821241	NG893231	NM742970	NG783255
Peak biomass (T):	2,500	2,500	1,350	2,500
No. of pens:	12	12	12	10
Pen dimensions:	120m	120m	80m	120m
Pen configuration:	2x6, 75m matrix	2x(2x3), 65m matrix	2x6, 65m matrix	2x5, 65m matrix

A treatment depth of 3.5m was chosen as a realistic net depth during application of the medicine for the 120m circumference pens at Ardintoul, Duich and Sron. The net dimensions were unknown for the 80m circumference pens at Earnsaig so a treatment depth matching the 160m pens of 5m was selected. Table 6 shows the total treatment mass used at each site. A total mass of 31.203 kg of azamethiphos was released from the cumulative modelling simulations. Each site followed the same treatment regime as Loch Hourn with 1 pen treatment per day except for Earnsaig which has an Azamethiphos consent that allows 2 pens to be treated per day, these were released 3 hours apart. The initial mass released per pen was set as the consented 24 hr limit for each neighbouring site, apart from Earnsaig where each pen released half of the 24 hour limit. The EQS was then applied, as before, 72 hours after the final treatments.

Table 6. Total mass of azamethiphos released from sites during the cumulative modelling simulations

Site	24 hr mass released (kg)	Total mass released (kg)
Loch Hourn	1.2300	9.840
Ardintoul	0.6877	8.252
Duich	0.5501	6.601
Earnsaig	0.7030	4.218
Sron	0.2292	2.292

Dispersion simulations were performed over neap and spring tides from 2019 (Figure 6, ID275) with parameters matching that of the baseline run performed for Loch Hourn only. The pen locations and medicine release times are listed in Table 7.

The start time of each site treatment was adjusted accordingly to allow for all sites to complete treatment at the same time on the same day so that the EQS could be applied. The model start day was then also shifted so that the neap and spring tides were still centred around the treatments at Loch Hourn. The simulations ran for 361 hours. This covered the treatment period (264 hours), a dispersion period to the EQS assessment after 336 hours (72 hours after the final treatment), and an extra 25 hours to check for chance concentration peaks, as done previously.

Table 7: Pen locations and treatment schedule for the cumulative modelling runs.

Pen	Site	Easting	Northing	Treatment Mass (kg)	Release Time Schedule (h)
1	Hourn	180043	809879	1.23	96
2	Hourn	179960	809935	1.23	120
3	Hourn	179877	809991	1.23	144
4	Hourn	179794	810046	1.23	168
5	Hourn	180374	809655	1.23	192
6	Hourn	180291	809711	1.23	216
7	Hourn	180208	809767	1.23	240
8	Hourn	180126	809823	1.23	264
1	Ardintoul	181991	824131	0.6877	0
2	Ardintoul	182004	824057	0.6877	24
3	Ardintoul	182065	824144	0.6877	48
4	Ardintoul	182078	824070	0.6877	72
5	Ardintoul	182138	824157	0.6877	96
6	Ardintoul	182151	824083	0.6877	120
7	Ardintoul	182212	824170	0.6877	144
8	Ardintoul	182225	824096	0.6877	168
9	Ardintoul	182286	824183	0.6877	192
10	Ardintoul	182299	824109	0.6877	216
11	Ardintoul	182360	824186	0.6877	240
12	Ardintoul	182373	824122	0.6877	264
1	Duich	189165	823254	0.5501	0
2	Duich	189220	823290	0.5501	24
3	Duich	189201	823200	0.5501	48
4	Duich	189255	823235	0.5501	72
5	Duich	189236	823145	0.5501	96
6	Duich	189291	823181	0.5501	120
7	Duich	189307	823037	0.5501	144
8	Duich	189362	823072	0.5501	168
9	Duich	189343	822982	0.5501	192
10	Duich	189397	823017	0.5501	216
11	Duich	189378	822928	0.5501	240
12	Duich	189433	822963	0.5501	264
1	Sron	178234	825630	0.2292	48
2	Sron	178234	825565	0.2292	72
3	Sron	178299	825630	0.2292	96
4	Sron	178299	825565	0.2292	120
5	Sron	178364	825630	0.2292	144
6	Sron	178364	825565	0.2292	168
7	Sron	178429	825630	0.2292	192
8	Sron	178429	825565	0.2292	216
9	Sron	178494	825630	0.2292	240
10	Sron	178494	825565	0.2292	264
1	Earnsaig	174204	797497	0.3515	141
2	Earnsaig	174270	797506	0.3515	144
3	Earnsaig	174221	797433	0.3515	165
4	Earnsaig	174288	797443	0.3515	168
5	Earnsaig	174243	797371	0.3515	189
6	Earnsaig	174306	797381	0.3515	192
7	Earnsaig	174261	797308	0.3515	213
8	Earnsaig	174328	797316	0.3515	216
9	Earnsaig	174279	797240	0.3515	237
10	Earnsaig	174344	797255	0.3515	240
11	Earnsaig	174302	797178	0.3515	261
12	Earnsaig	174367	797189	0.3515	264

The simulation used ~ 1.2 million numerical particles in total, each particle representing 20 mg of azamethiphos. The particles represented double the mass of azamethiphos in the standard Loch Hourn model runs due to required computational power.

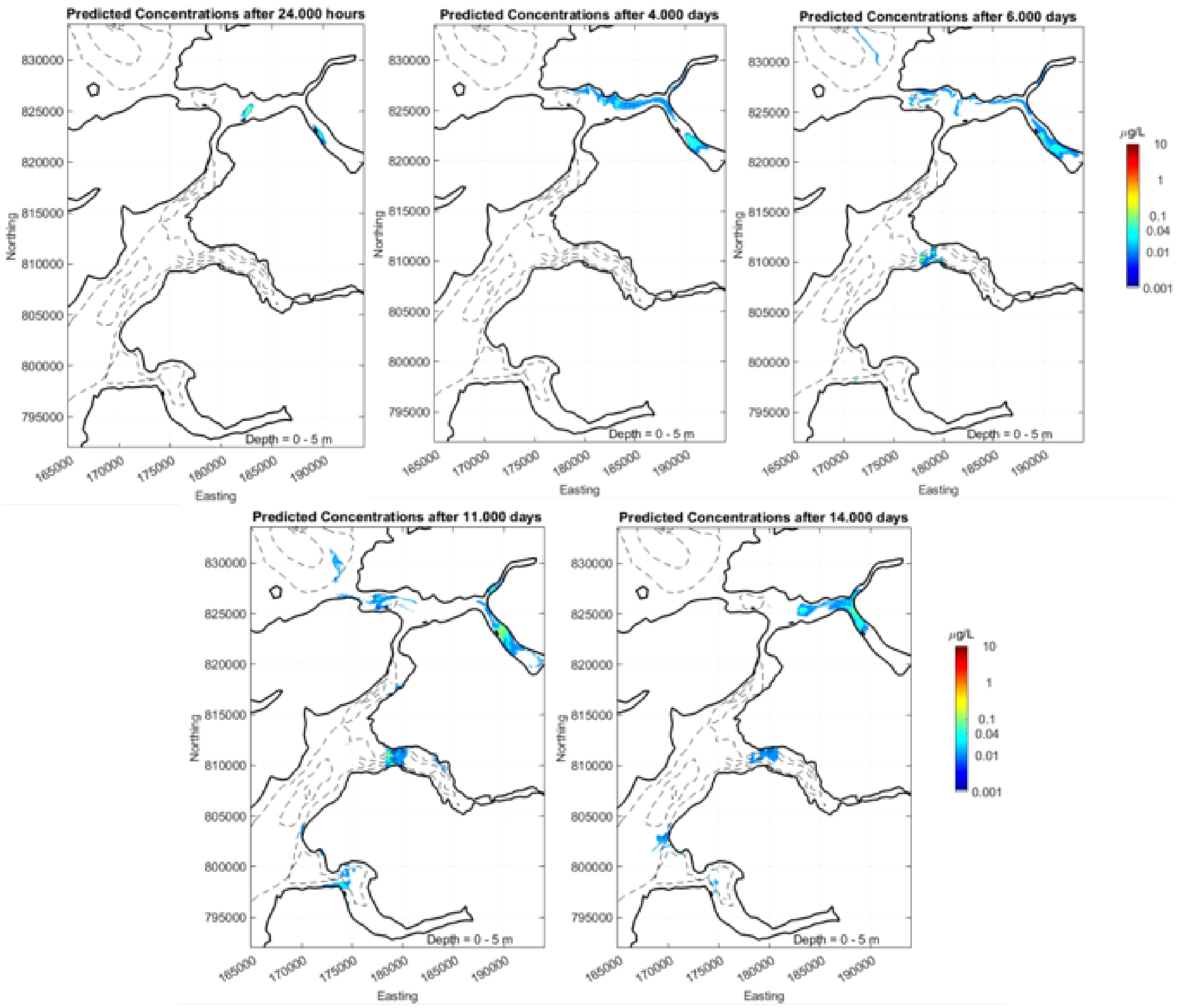

Figure 17: Dispersion simulation over neap tide of Loch Hourn and its neighbouring sites following the treatment schedule described in Table 7. Start day = 18. The pens for each site are marked (O).

Figure 17 shows the dispersion simulation with the neap tide. After 24 hours, as the second days treatment was discharged at Ardintoul and Duich, patches of medicine are evident. The maximum concentration at this time was ~120 µg/L, due to the release of the second treatment. After 4 days, the first 5 treatments have already been released from Duich and Ardintoul and the first 3 treatments have been released from Sron when the first treatment is released from Hourn. 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 6 days, the treatments have continued to be released at Ardintoul, Duich, Sron and Loch Hourn and the first of two daily treatments at Earnsaig has now also been released. Patches of medicine are now evident in Loch Hourn and Loch Nevis. At 11 days, the treatments at all sites have completed, however the peak concentration is still at ~120 µg due to the final release from each site. At the EQS time of 14 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 Loch Hourn does not interact with any of the neighbouring sites discharged medicine patches.

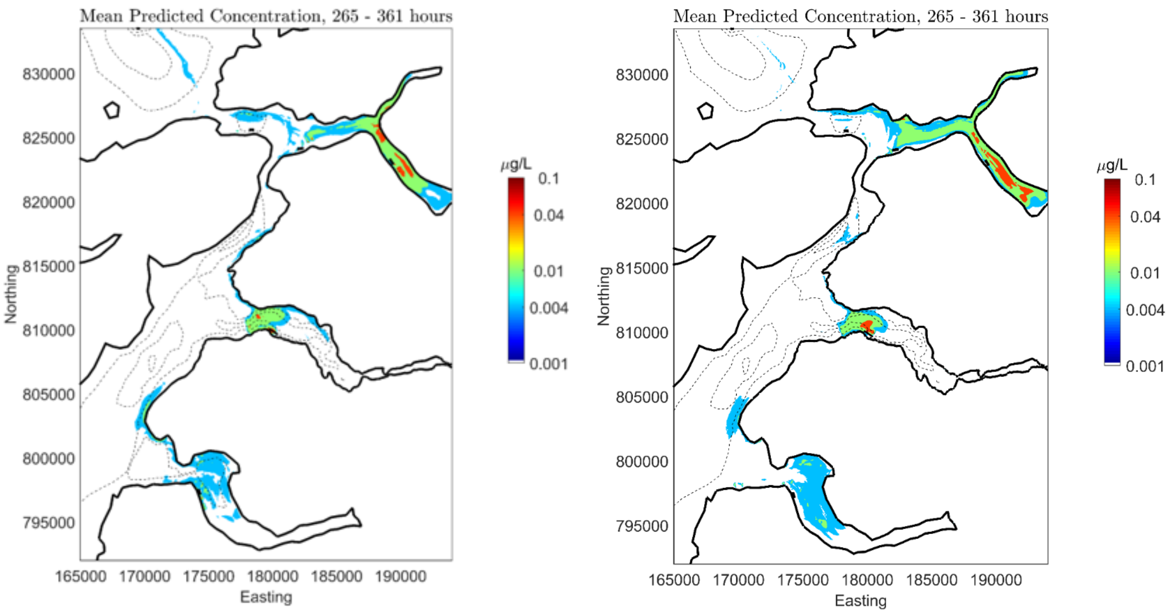

Figure 18: Mean predicted concentrations over the last 96 hours of the treatment scenario described in Table 7 over neap tide (left) and spring tide (right).

Figure 18 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 all sites over neap and spring tides are shown in Figure 19 and Figure 20 respectively. In the neap simulation (Figure 19), the medicine release from Earnsaig causes a MAC breach while those from Loch Duich cause both a MAC and EQS breach. The same is observed in the spring simulation, and additionally there is both an EQS and MAC failure from the Ardintoul treatment releases. Site-specific modelling would need to be undertaken at Duich, Ardintoul and Earnsaig to inspect the medicine dispersion in more detail; however, since this report focuses on Loch Hourn, and the treatments from Loch Hourn clearly do not interact with those from other sites (Figure 18), further modelling of other sites was not undertaken.

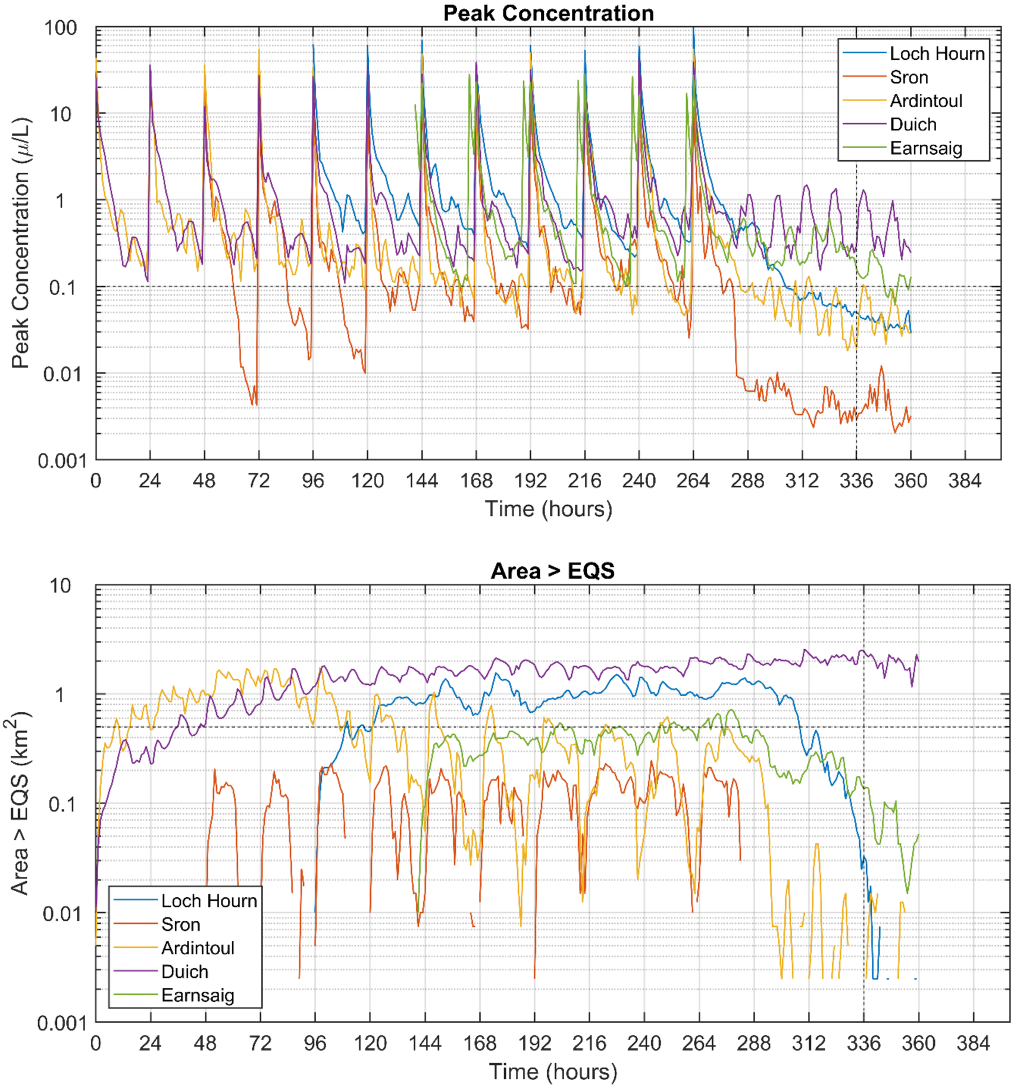

Figure 19: Time series of maximum concentration (top) and area exceeding the EQS (bottom) for the cumulative modelling of all sites over neap tide (STARTDAY = 18). The MAC and area limits 72 hours after the final treatment (Time = 336 hours) of 0.1 µg/L and 0.5 km^2 respectively are indicated by the horizontal dashed lines.

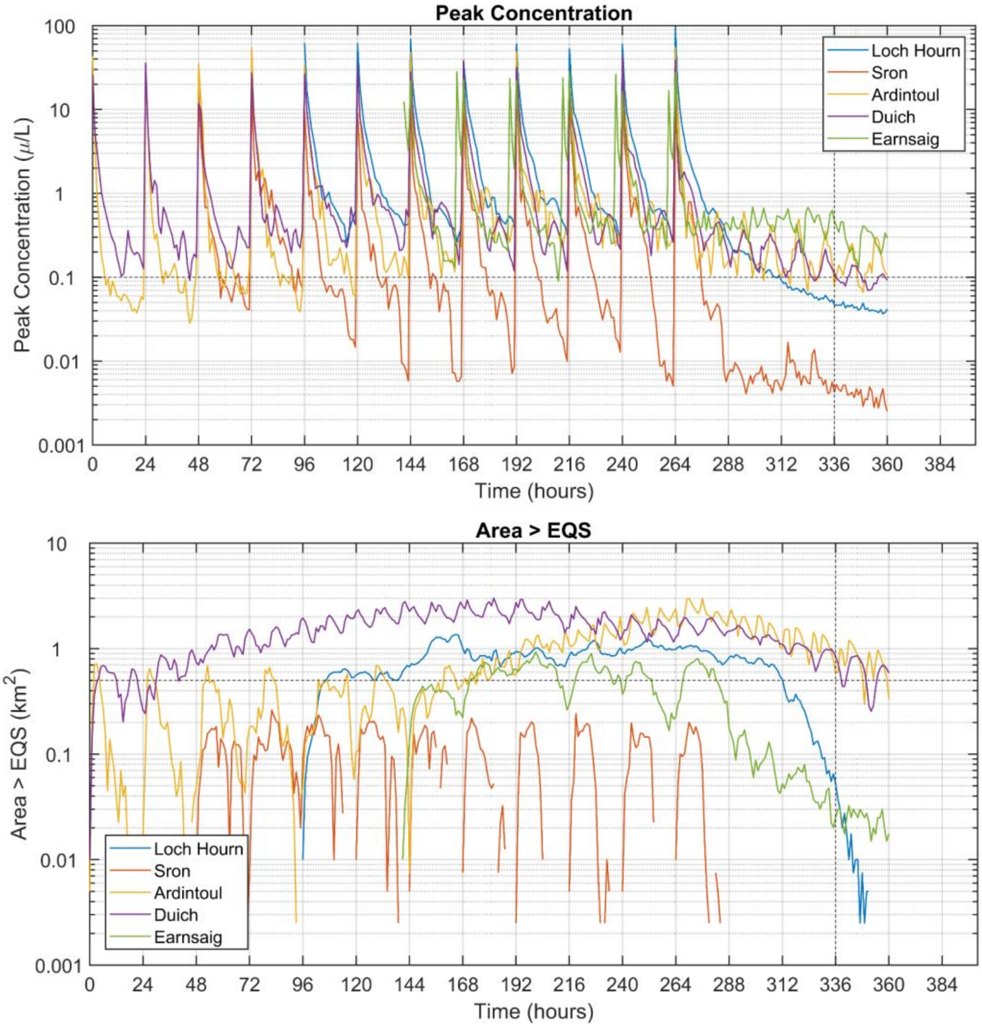

Figure 20: Time series of maximum concentration (top) and area exceeding the EQS (bottom) for the cumulative modelling of all sites over spring tide (STARTDAY = 10). The MAC and area limits 72 hours after the final treatment (Time = 336 hours) of 0.1 µg/L and 0.5 km² respectively are indicated by the horizontal dashed lines.

5 SUMMARY AND CONCLUSIONS

A total of 29 dispersion simulations have been performed to assess whether bath treatments at Loch Hourn salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 1.23 kg of azamethiphos for treatment, resulting in a total discharge over 8 days of 9.84 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 8.

Table 8. Summary of Results

SITE DETAILS			
Site Name: Site location: Peak biomass (T):		Creag an T'Sagairt Loch Hourn 3,100	
PEN DETAILS			
Number of pens: Pen dimensions: Working Depth (m): Pen group configuration:		8 160m Circumference 20 1 x 8, 100m matrix	
HYDROGRAPHIC SUMMARY		**ID246**	**ID275**
Surface Currents	**Hourn**	**Sep-Nov 2018**	**Apr-Jul 2019**
	Mean Speed (m/s)	0.066	0.042
	Residual Speed (m/s)	0.040	0.018
	Residual Direction (°G)	330	277
	Tidal Amplitude Parallel (m/s)	0.091	0.066
	Tidal Amplitude Normal (m/s)	0.026	0.025
	Major Axis (°G)	330	295
BATH TREATMENTS			
Recommended consent mass - 3hr Azamethiphos (kg)		1.23	
Recommended consent mass - 24hr Azamethiphos (kg)		1.23	

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 1.23 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 criteria were met. Simulations over two different neap tides from 2018 and 2019 demonstrated that the modelled treatment regime consistently complied with the relevant EQS. For the simulation during spring tides, greater dispersion meant that the MAC and EQS were met very comfortably. Therefore, we believe that the requested daily quantity of 1.23 kg of azamethiphos can be safely discharged without breaching the MAC or EQS.

The cumulative modelling that was undertaken for Loch Hourn and four neighbouring sites indicated that if all sites were treated simultaneously, there was no interaction between the medicine plumes. The time series plotted for these simulations show that Loch Hourn does not contribute towards the failures seen at Earnsaig, Ardintoul and Duich.

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 10.

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