Azamethiphos Dispersion Modelling Carradale (South), Kilbrannan Sound CAR/L/1078064

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Carradale (South) salmon farm will comply with pertinent Environmental Quality Standards (EQS). A realistic treatment regime, with 1 pen treatment per day was simulated. Each pen required g of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) for treatment, resulting in a daily release of 652 g and a total discharge over 5 days of 4.0 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 652 g of azamethiphos should comfortably comply with the EQS. The peak concentration during the baseline simulation 72 hours after the final treatment was less than 0.1 µg L^{-1}, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg L^{-1} was substantially less than the allowable 0.5 km^2 for both sites. 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:	Carradale (South)
Site Location:	Kilbrannan Sound
Peak Biomass (T):	2,500
Pen Details	
Number of Pens:	6
Pen Circumference (m):	160
Working Depth (m):	16
Pen Group Configuration:	2 x 3
Azamethiphos Consent	
Recommended 3-hour (g):	652
Recommended 24-hour (g):	652

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 increase the current consent of topical sea lice veterinary medicines at the marine salmon farm Carradale (South), Kilbrannan Sound (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 January 2022 (SEPA, 2022).

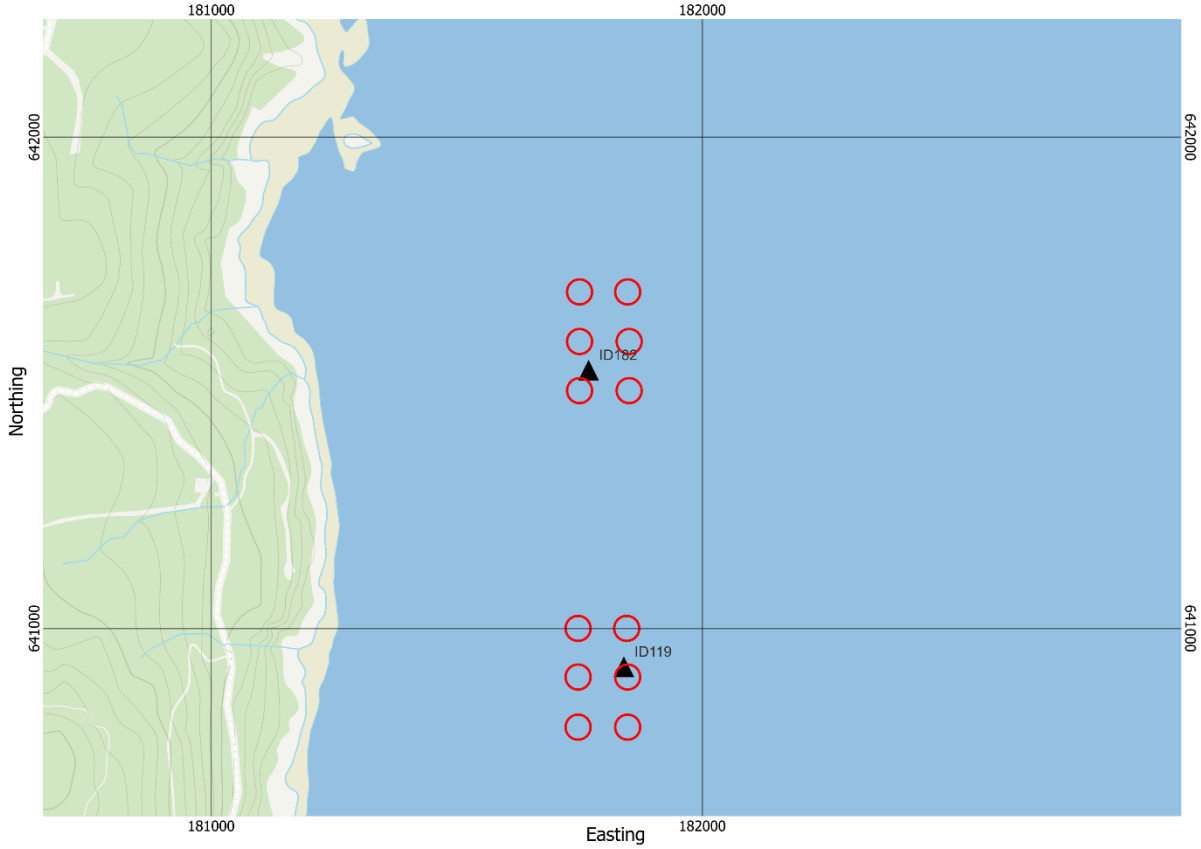

Figure 1. Location of the two salmon farms, Carradale North (upper group) and the neighbouring site Carradale (South) (lower group) and the location of the ADCP deployments (▲) relative to the pen positions (o).

1.1 Site Details

The site is situated toward the mid part of Kilbrannan Sound north of Carradale port(Figure 1). Details of the hydrographic data are provided in Table 2. The receiving water is defined as open water. Carradale (South) has a neighbouring site, Carradale North (Figure 1).

Table 2. Hydrographic Information

Hydrographic Data		
	ID119	**ID182**
Site:	Carradale (South)	Carradale North
Current Meter Position:	181840E 640922N	181768E 641526N
Depth of Deployment Position (m):	45.66	41.51
Surface Bin Centre Height Above Bed (m):	39.72	34.72
Middle Bin Centre Height Above Bed (m):	29.72	25.72
Bottom Bin Centre Height Above Bed (m):	2.72	2.72
Duration of Record (days):	63	60
Start of Record:	30/09/2016 10:30	07/08/2017 13:00
End of Record:	08/12/2016 08:50	06/10/2017 07:20
Current Meter Averaging Interval (min):	20	20
Magnetic Correction to Grid North:	-3.32	-3.18

2. MODEL DETAILS

2.1 Model Selection

The modelling approach adopted a coupled hydrodynamic and particle tracking method, whereby water currents in the region, modelled using a calibrated hydrodynamic model, advected particles representing the topical medicine around the model domain. Turbulent eddy diffusion was modelled using a random walk method. Outputs from the modelling were derived to assess the dispersion of the medicine following treatments against statutory EQS. The modelling approach is described in full in the Hydrodynamic Model Description (Mowi Scotland Ltd, Carradale Hydrodynamic Model Description, December 2023), 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, 2022) was used. The model used the hydrodynamic flow fields from the RiCOM model simulations. This model has been used previously to simulate sea lice dispersal (Gillibrand & Willis, 2007), the development of a harmful algal bloom (Gillibrand et al., 2016a) and the dispersion of

cypermethrin from a fish farm (Willis et al., 2005). The approach for veterinary medicines is the same as for living organisms, except that medicine has no biological behaviour but instead undergoes chemical decay: the numerical particles in the model represent “droplets” of medicine of known mass, which reduces over time at a rate determined by a specified half-life. Particles are released at pen locations at specified times, according to a treatment schedule. The number of particles combined with their initial mass represents the mass of medicine required to treat a pen. The particles are then subject to advection, from the modelled flow fields, horizontal and vertical diffusion, and chemical decay. Concentrations of medicine can be calculated throughout the simulation and compared with relevant EQS e.g. 72 hours after the final treatment. Here, the dispersion of azamethiphos following treatment scenarios at Carradale (South) has been modelled to illustrate the quantities of medicine that disperse safely in the environment.

2.2 Model Domain and Boundary Conditions

The unstructured mesh used in the model was adapted from the Firth of Clyde sub-model mesh of the Scottish Shelf Model (SSM; Marine Scotland, 2016) (Figure 2). Model resolution was enhanced in the Kilbrannan Sound region particularly around the Mowi sites at Carradale North and Carradale (South) (Figure 3). The spatial resolution of the model varied from 18m in some inshore waters to 3km along the open boundary. The model consisted of 68,390 nodes and 130,139 triangular elements. Bathymetry was taken from The Firth of Clyde model and local multibeam surveys (Figure 4). Given that topical medicine dispersion occurs in the upper water column, it was not deemed necessary to use highly detailed bathymetry data in the immediate vicinity to the pens.

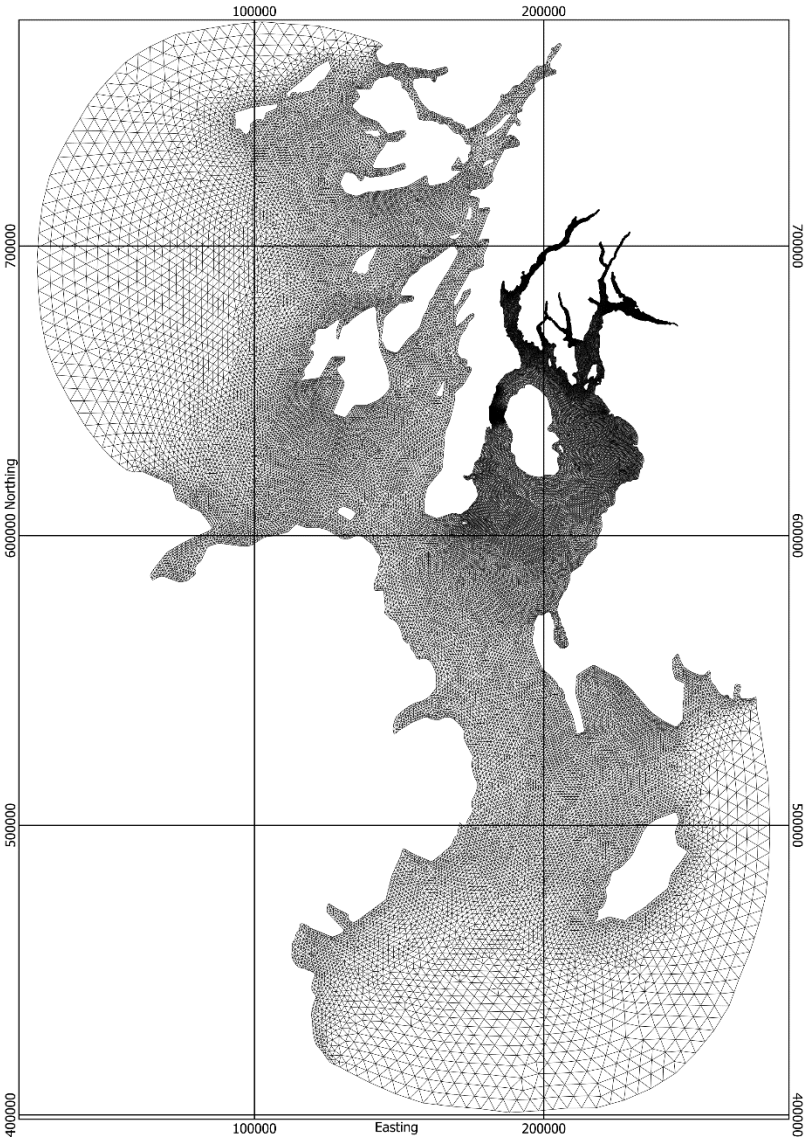

Figure 2. The mesh and domain of the modelling study, adapted from The Firth of Clyde sub-model.

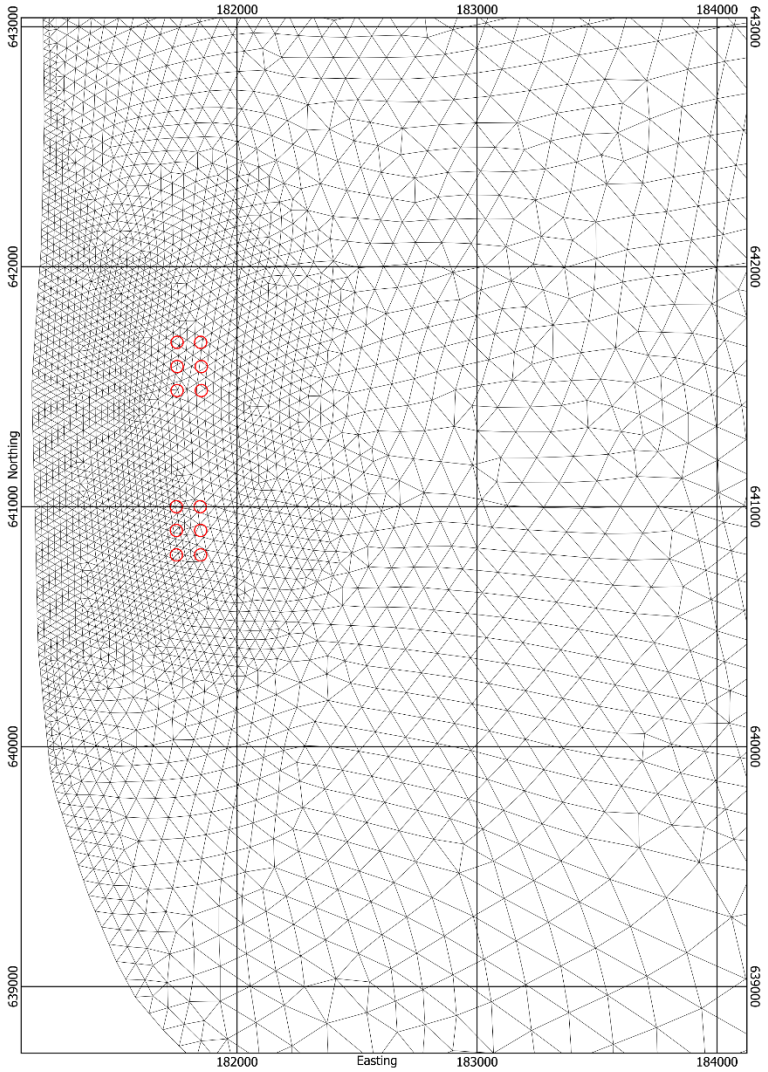

Figure 3. The unstructured mesh around the Carradale sites in the modified model grid, with the proposed cage locations indicated (○).

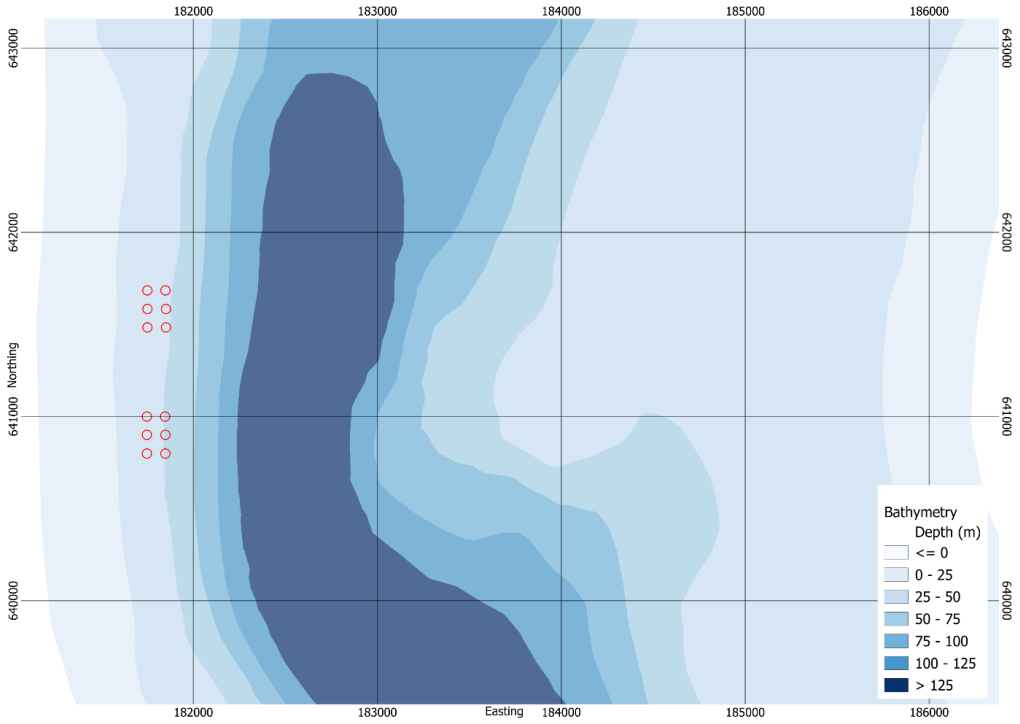

Figure 4. Model water depths (m) in the area around the Carradale sites. The pen locations indicated (○). Carradale North (upper group) and Carradale (South) (lower group).

The model is forced at the outer boundaries by 12 tidal constituents (M_2, S_2, N_2, K_2, O_1, K_1, P_1, Q_1, M_4, MU_2, L_2, MS_4) which were derived from tidal analysis (Pawlowicz et al., 2002) of the sea surface elevations at the closest nodes from the Scottish Shelf Model climatology (Marine Scotland, 2016). Spatially- and temporally-varying wind speed and direction data are taken from the ERA5 global reanalysis dataset (ECMWF, 2021) for the required simulation periods.

Full details of the calibration and validation of the hydrodynamic model are given in the Carradale Hydrodynamic Model Description (Mowi Scotland Ltd, 2023).

2.3 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the UnPTRACK model (Gillibrand, 2022), 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 12 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 3.2 m was chosen as a realistic net depth during application of the medicine for the 160m pens. The initial mass released per pen was calculated from the reduced pen volume and a treatment concentration of 100 µg L^{-1}, with a total mass of 4.0 kg of azamethiphos released during treatment (6 pens). Particles were released from random positions within a pen radius of the centre and within the 0 – 3.2 m depth range. The simulations used *ca. 782,280* numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation ran for a total of 216 hours (9 days). This covered the treatment period (120 hours), a dispersion period to the EQS assessment after 72 hours after the final treatment, and an extra 24 hours to check for chance concentration peaks. At every hour of the simulation, particle locations and properties (including the decaying mass) were stored and subsequently concentrations calculated. Concentrations were calculated on a grid of 25 m x 25 m squares using a depth range of 5 m. Using a regular grid for counting makes calculating particle concentrations and presenting the results easier , and also provides consistent accuracy and precision in the calculated concentrations across the grid.

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

(i) The maximum concentration (µg L^{-1}) anywhere on the regular grid; and
(ii) The area (km^2) where the EQS was exceeded.

These results were used to assess whether the EQS or MAC was breached after the allotted period (72 hours after the final treatment).

Sensitivity analyses were conducted to assess the effects of:

(i) Medicine half-life
(ii) Horizontal diffusion coefficient, K_H
(iii) Vertical diffusion coefficient, K_V
(iv) Time of release

The dispersion simulations were performed separately over neap and spring tides during 2016 (ID119) (Figure 5). A further set of simulations were performed over neap tides in 2017 (ID182) to confirm the adequacy of dispersion during the weakest tides (Figure 6).

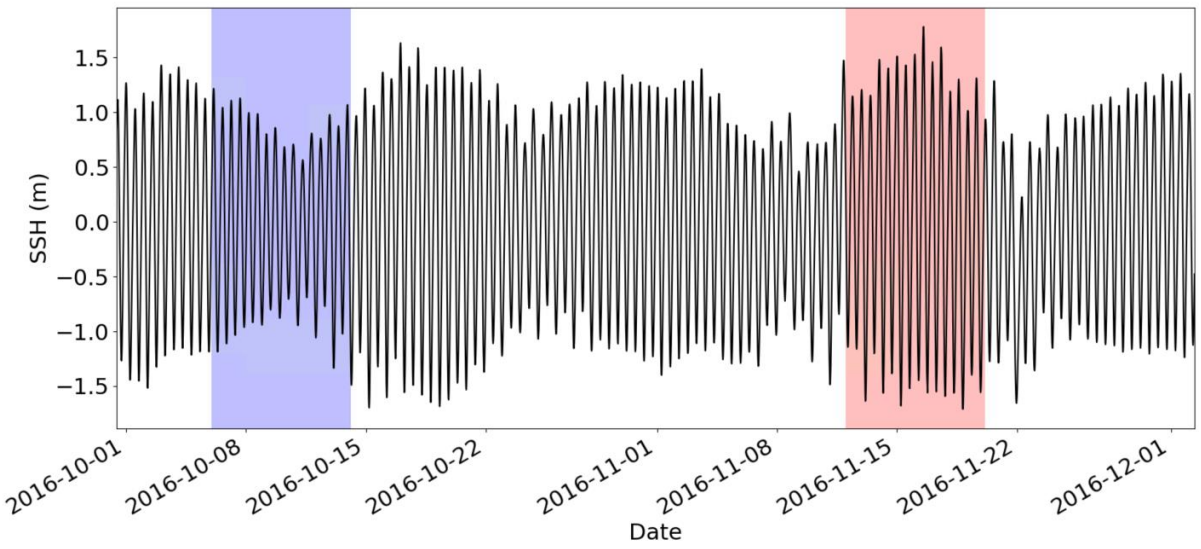

Figure 5. Sea surface height (SSH) at Carradale (South) from 30th September 2nd December 2016 (ID119). Dispersion simulations were performed over periods of neap tides (blue, start day 6th October 2016) and spring tides (red, start day 12th November 2016)

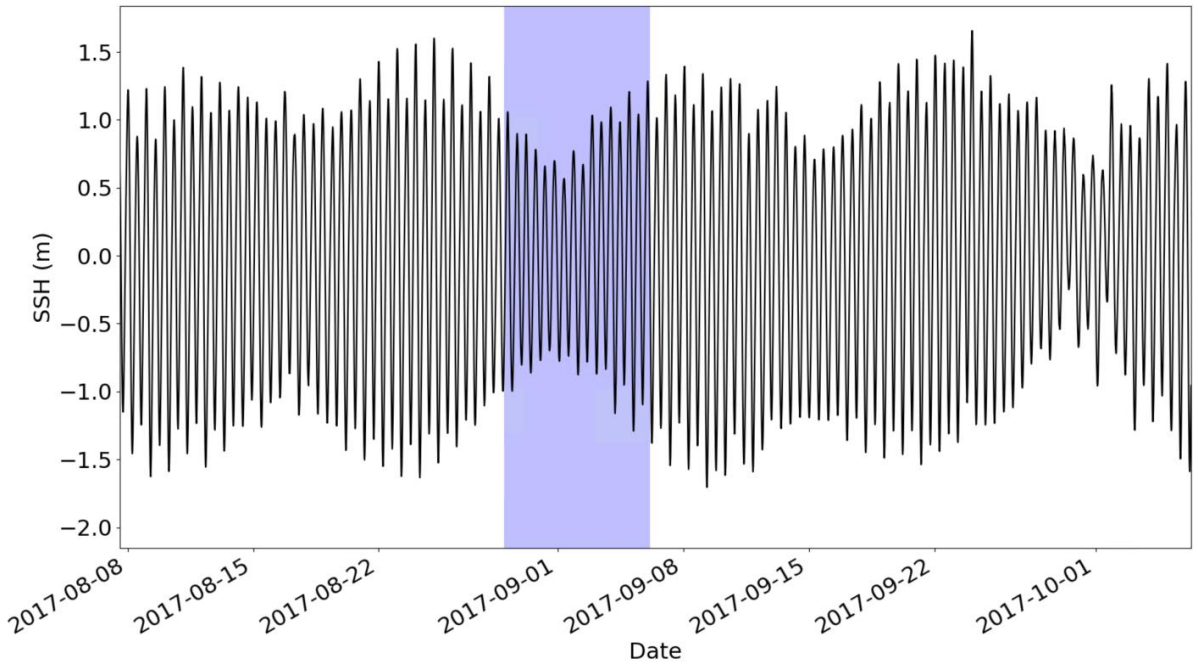

Figure 6. Sea surface height (SSH) at Carradale North from 7th August 2017 – 6th October 2017 (ID182). Dispersion simulations were performed over periods of neap tides (blue, start day 25th September 2017).

2.4 Medicine Dispersion Simulations

The pen locations and details of the medicine source are listed in Table 3. The time of release is relative to the start of the neap or spring period highlighted in Figure 5 and Figure 6.

All simulations used the release schedule and quantities outlined in Table 3. In Runs 2 – 7 (Table 4), the release schedule was set back or forward by a number of hours to investigate the effect of tidal state at the time of release on the results. Results for these simulations are still presented in terms of time relative to the first release.

Table 3. Details of the treatment simulated by the dispersion model. The release time is relative to the start of the neap or spring period highlighted in Figure 5 and Figure 6.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (g)	Release Time (hr)
1	181747	641000	3.2	652	0
2	181846	641000	3.2	652	24
3	181747	640901	3.2	652	48
4	181848	640901	3.2	652	72
5	181747	640799	3.2	652	96
6	181848	640799	3.2	652	120

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

Set	Run No.	$T_{1/2}$ (h)	K_H	K_V	Start Time
Neap Tides, Start day = 5 (6th October 2016, ID119)					
Baseline	1	134.4	0.1	0.001	00:00
1	2	134.4	0.1	0.001	00:00 -6h
	3	134.4	0.1	0.001	00:00 -4h
	4	134.4	0.1	0.001	00:00 -2h
	5	134.4	0.1	0.001	00:00 +2h
	6	134.4	0.1	0.001	00:00 +4h
	7	134.4	0.1	0.001	00:00 +6h
2	8	134.4	0.2	0.001	00:00
	9	134.4	0.03	0.001	00:00
3	10	134.4	0.1	0.0025	00:00
	11	134.4	0.1	0.005	00:00
Spring Tides, Start day = 44 (12th November 2016, ID119)					
5	12	134.4	0.1	0.001	00:00
6	13	134.4	0.2	0.001	00:00
	14	134.4	0.03	0.001	00:00
7	15	134.4	0.1	0.0025	00:00
	16	134.4	0.1	0.005	00:00
Neap Tides, Start day = 23 (29th August 2017, ID182)					
8	17	134.4	0.1	0.001	00:00
9	18	134.4	0.2	0.001	00:00
	19	134.4	0.03	0.001	00:00
10	20	134.4	0.1	0.0025	00:00
	21	134.4	0.1	0.005	00:00

2.5 3-hour EQS

In addition to the main simulations described above to assess compliance with the 72-hour EQS, simulations were also performed to assess compliance with the 3-hour EQS (SEPA, 2022). The 3-hour EQS is applied as a mixing zone EQS, whereby the area where concentrations exceed the EQS of 250 ng L^{-1} after 3 hours must be less than the 3-hour mixing zone. The 3-hour mixing zone is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 14.7 cm s^{-1} was used from ID119 (Table 5).

Table 5. Parameter values used in the calculation of the 3-hour mixing zone ellipse area and the resulting area

Parameter	Value
Mean current speed (ms^{-1})	0.147
Area of 160m pen (km^2)	0.001446
Distance from shore (km)	0.460
Mean water depth (m)	45.4
Treatment Depth (m)	3.2
Mixing zone ellipse area (km^2)	**0.231802**

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 10 m x 10 m grid (rather than a 25 m x 25 m grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

2.6 Interactions with Special Features

One nearby Marine Protected Area (South Arran) has been identified (SEPA 2023) (Figure 7) which are thought to be at potential risk from medicine influence and hence must be considered when modelling the treatment releases from Carradale (South).

Predicted concentrations of azamethiphos within the Shellfish Areas during the simulation periods will be extracted, and the mean and maximum concentrations derived. The proportion of the PMF where the 3-hour (0.25 µg L^{-1}) and the 72-hour (0.10 µg L^{-1}) EQS are exceeded will be calculated. These calculations will be undertaken for a 5 m thick layer immediately above the seabed, since these special features are predominantly benthic habitats.

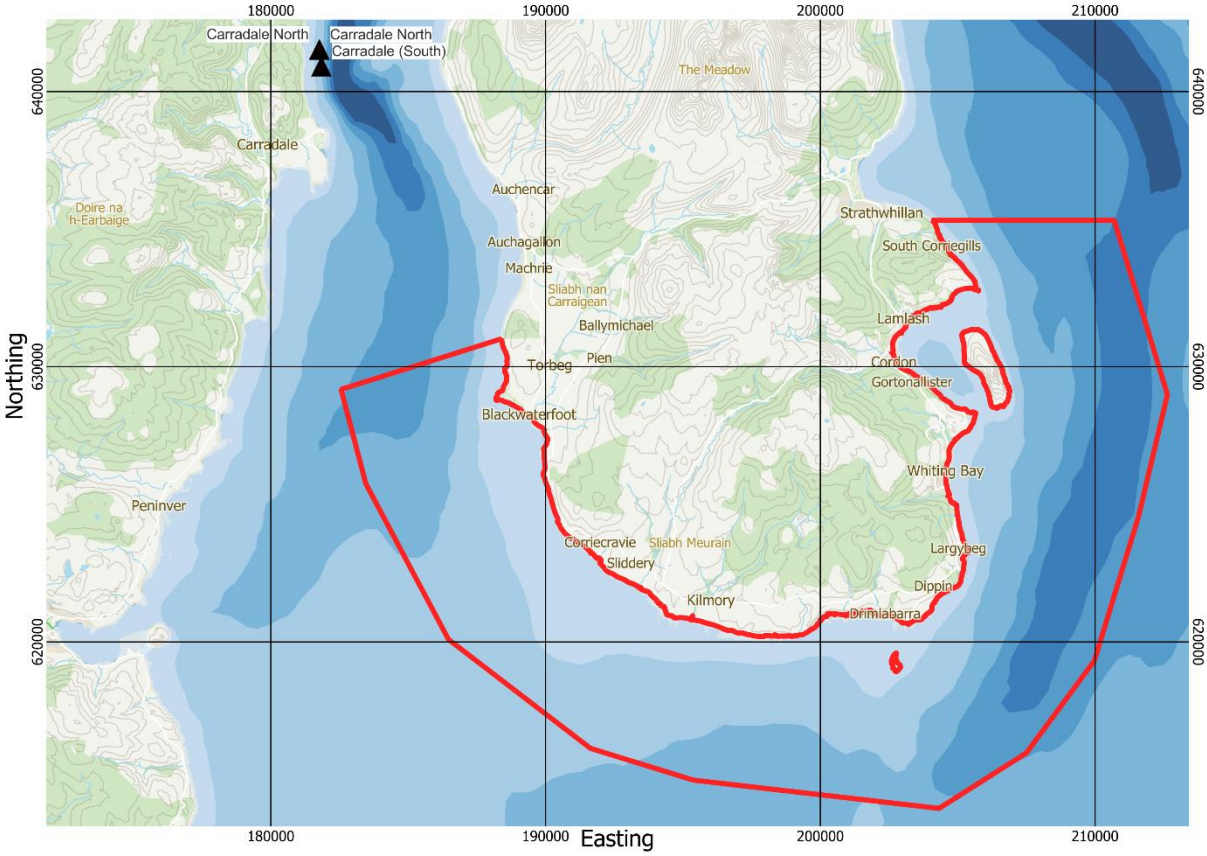

Figure 7. South Arran Marine Protected Area near the Carradale sites.

2.7 Diffusion Coefficients

Selection of the horizontal diffusion parameter, K_H, was guided by dye releases conducted at Carradale North and Carradale (South) by Anderson Marine Surveys Ltd. between 12th and 13th March 2017, along with several other dye release studies undertaken at other salmon farm locations. Dye tracking studies proceed by releasing a known quantity of dye into the sea, and then attempting to map the resulting dye patch as it disperses over time by deploying a submersible fluorometer from a boat. Each survey of the patch takes a finite amount of time (typically less than 30 minutes) and is usually made up of several transects which attempt to criss-cross the patch. An estimate of horizontal diffusivity can be made from each transect, but the location of the transect relative to the centre of the patch (and the highest concentrations) is often uncertain. The estimates of horizontal diffusivity shown in Figure 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 at the Carradale sites gave a mean horizontal diffusivity of 0.03 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.

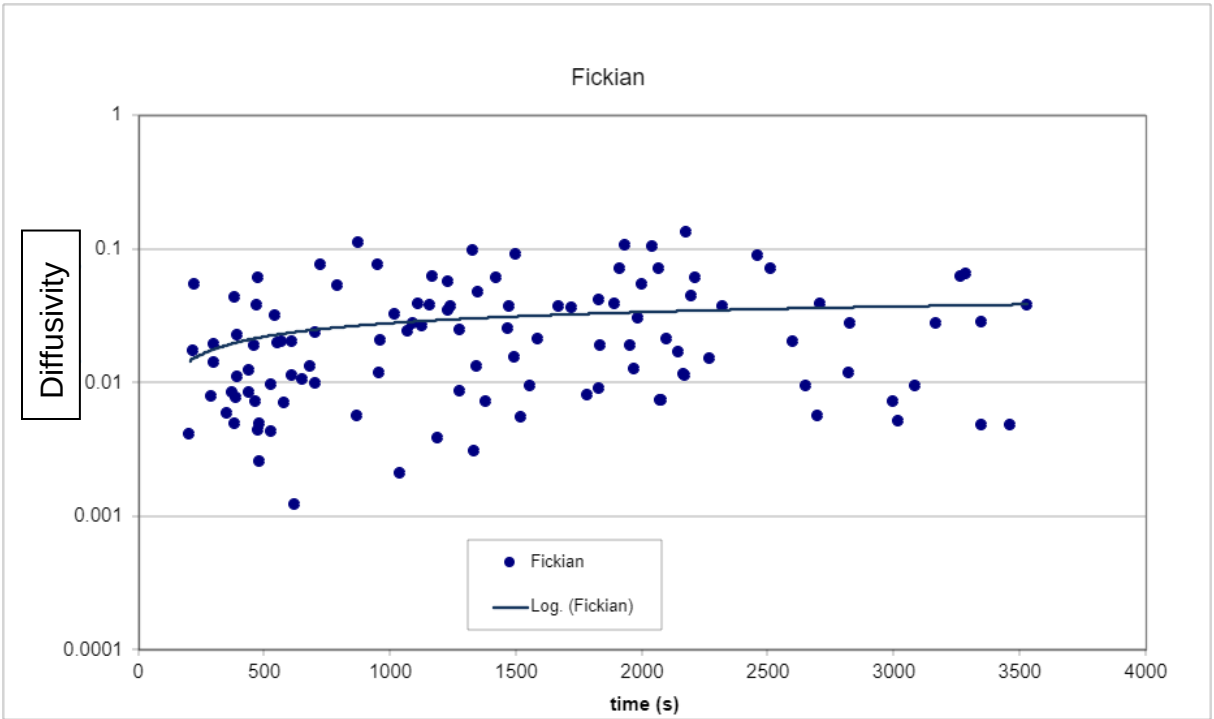

Figure 8. Estimated horizontal diffusivity (m^2 s^{-1}) from dye release experiments at the Carradale sites. The mean diffusivity was 0.03 m^2 s^{-1}.

A second method of analysis is also presented here. According to Fickian diffusion theory (Lewis, 1997), the maximum concentration, C_{max} in a patch of dye decreases with time according to:

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

where M is the mass (kg) of dye released, H is a depth of water (m) over which the dye is assumed to mix vertically, K is the horizontal diffusivity (m^2 s^{-1}), assumed equal in x- and y-directions, and t is the time elapsed since release (s). The maximum concentration measured during each post-release survey should fall according to Equation (1) and allow an estimate of K to be made.

A number of dye releases have been conducted for Mowi Scotland Ltd in recent years to assess horizontal diffusivity at salmon farm sites. The maximum concentration measured in each post-release survey was identified (each comprised of a number of individual transects) and was then plotted against the nominal time for that survey (typically accurate to ±15 minutes). The results are shown in Figure 9. A nominal mixed depth of H = 5 m 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.

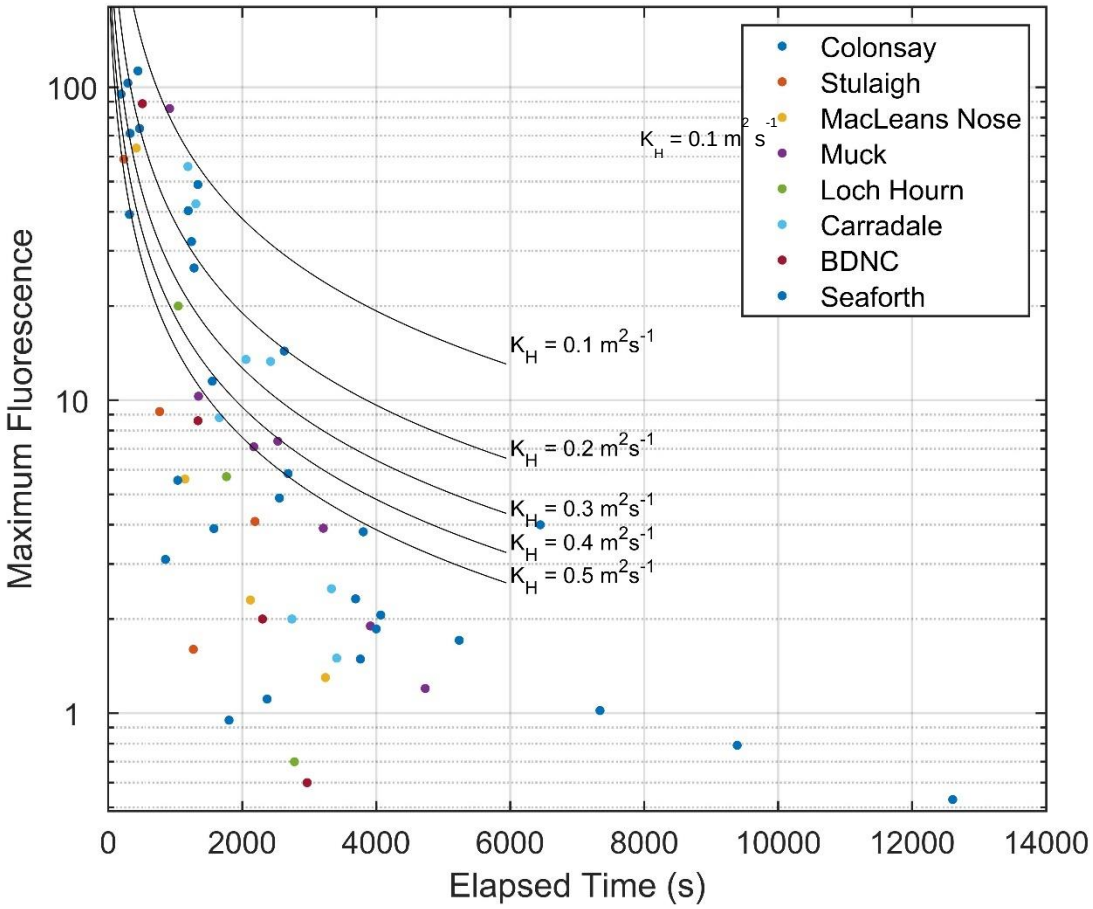

Figure 9. Maximum fluorescence measured following dye releases at a number of Mowi sites including Carradale. The top black line indicates the rate at which the maximum concentration would fall at a fixed horizontal diffusivity of K_H = 0.1 $m^2 s^{-1}$; maximum concentrations fall quicker (i.e. are below the line) if effective K_H > 0.1 $m^2 s^{-1}$.

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, October 2016 (ID119)

A standard treatment of 6 x 160 m pens, with a reduced net depth of 3.2 m and assuming 1 pen could be treated per day at a treatment concentration of 100 µg L^{-1}, resulted in a treatment mass per pen of azamethiphos of 652 g, a daily (24-hour) release of the same mass of 652 g and a total treatment release of 4.0 kg over 120 hours. The dispersion of the medicine during and following treatment from Run001 (Table 4) is illustrated in Figure 10. After 24 hours, as the second treatment on day 2 was discharged, discrete patches of medicine are evident from the first treatment release from the first day. The maximum concentration at this time is about 100 µg L^{-1}, due to the release of the second treatment. After 72 hours, as the treatment is discharged, discrete patches of medicine from the previous treatment releases are still evident, but the patches of medicine have rapidly dispersed and are already down to concentrations of the same order as the EQS (0.04 µg L^{-1}). Again, the maximum concentration at this time was approximately 100 µg L^{-1}, due to the release of the fourth treatment.

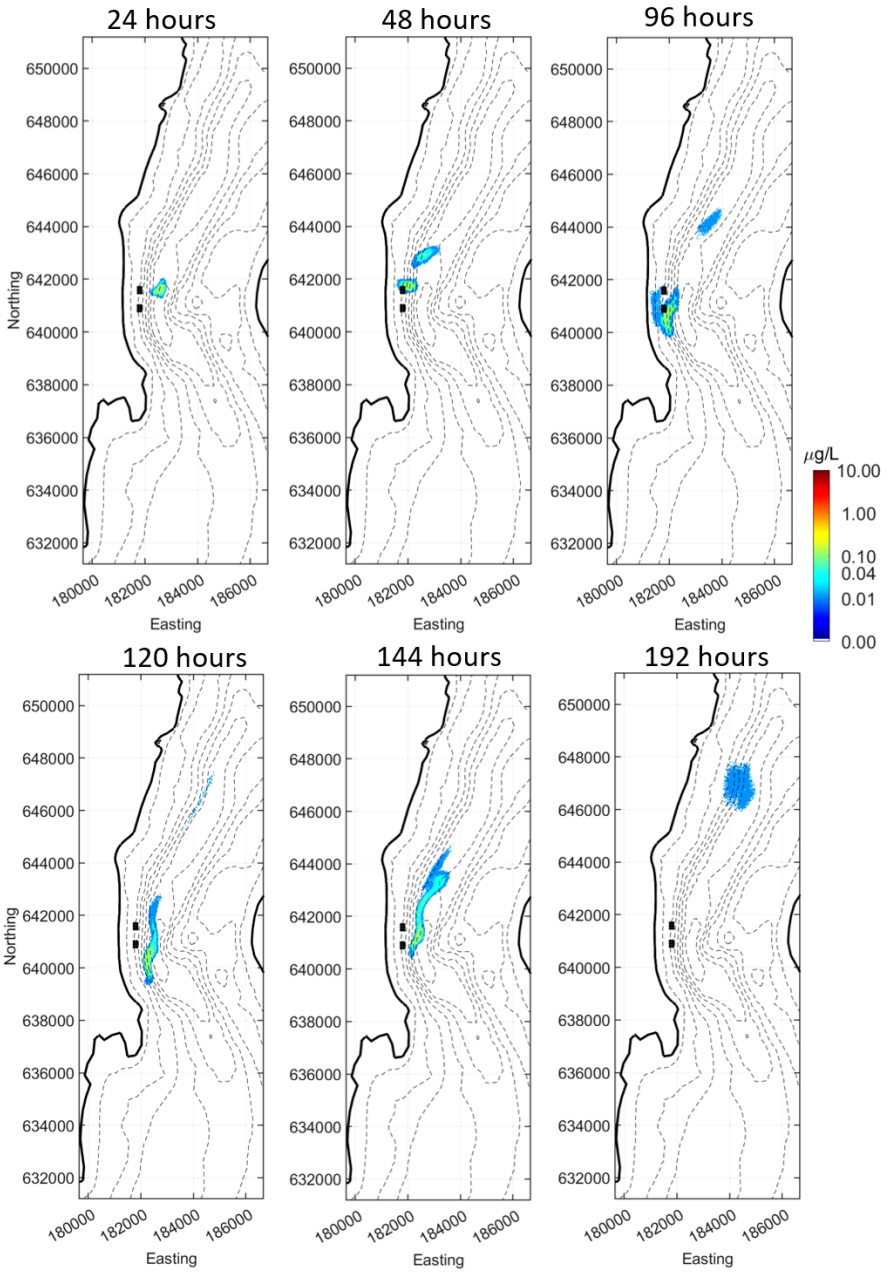

Figure 10. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 48 hours (top middle), 96 hours (top right), 120 hours (bottom left), 144 hours (bottom middle) and 192 hours (bottom right).

The treatment schedule completed after 120 hours (5 days). At this stage, the medicine released on earlier days had already dispersed North-Eastwards in Kilbrannan Sound. It is noticeable that dispersion of the medicine does not happen in a gradual “diffusive” manner, but is largely driven by eddies and horizontal shear in the spatially-varying velocity field, which stretches and distorts the medicine patches and enhances dispersion. Following the final treatment at 120 hours, the treatment patches were rapidly dispersed and concentrations rapidly fell away below the EQS. Remnants of medicine are seen North East of the Carradale sites in North Kilbrannan but at concentrations below the MAC.

The time series of maximum concentration from this simulation is shown in Figure 11. The 6 peaks in concentration of ~100 µg L^{-1} following each treatment event over the first 5 days are evident. Following the final treatment after 120 hours, the maximum concentration fell steadily away (Figure 11). A default half-life of 134.4 hours (5.6 days) was used. The maximum concentration seventy-two hours after the final treatment (time = 192 hours) was below 0.1 µg L^{-1}, the maximum allowable concentration (MAC).

The area where the EQS of 0.04 µg L^{-1} was exceeded peaked at about 0.4 km^2 following the final treatment, but had fallen below 0.5 km^2 within 48 hours of the final treatment; by 72 hours after the final treatment, the exceeded area was close to zero (Figure 11).

These results indicate that, with a horizontal diffusion coefficient of 0.1 m^2 s^{-1}, and a medicine half-life of 134.4 h, the EQS 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.

3.2 Sensitivity to Diffusion Coefficients

The model results were tested for sensitivity to the horizontal and vertical diffusion coefficients used. The horizontal diffusion coefficient used for the standard runs was K_H = 0.1 m^2 s^{-1}. Simulations were also performed with lower and higher values of K_H, specifically K_H = 0.2 m^2 s^{-1} and K_H = 0.03 m^2 s^{-1} (Table 4). The time series of maximum concentration and area exceeding the EQS are shown in Figure 11. The time series confirm that the MAC was only exceeded after 192 hours (72 hours after the final treatment) when K_H = 0.03 m^2 s^{-1} , which is considered an extremely very low value for the horizontal diffusion coefficient. The area limit of 0.5 km^2 was also comfortably met in all cases.

Similarly, sensitivity to the vertical diffusion coefficient, K_V, was tested (Figure 12). The model results are not particularly sensitive to the vertical diffusion rate, but increased vertical diffusion, likely in the presence of wind and/or waves, led to slightly smaller areas where the EQS was exceeded.

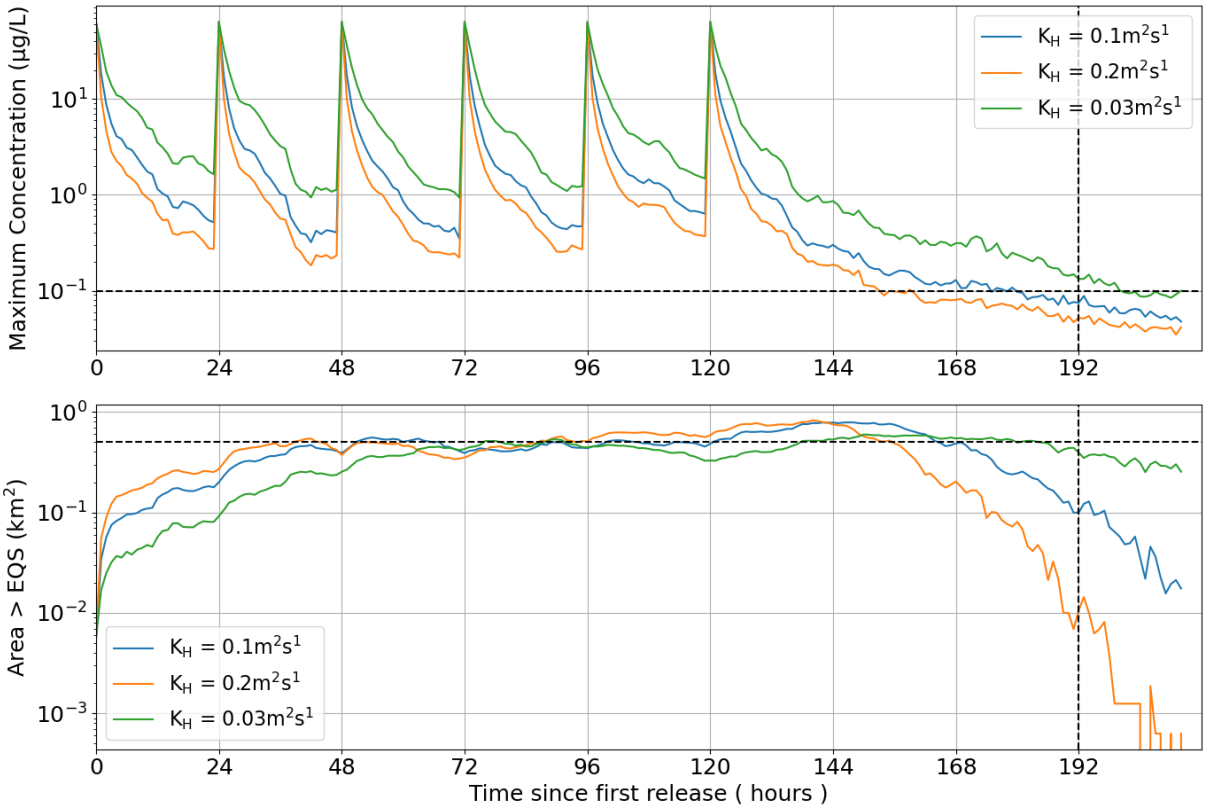

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient K_H ($m^2\ s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

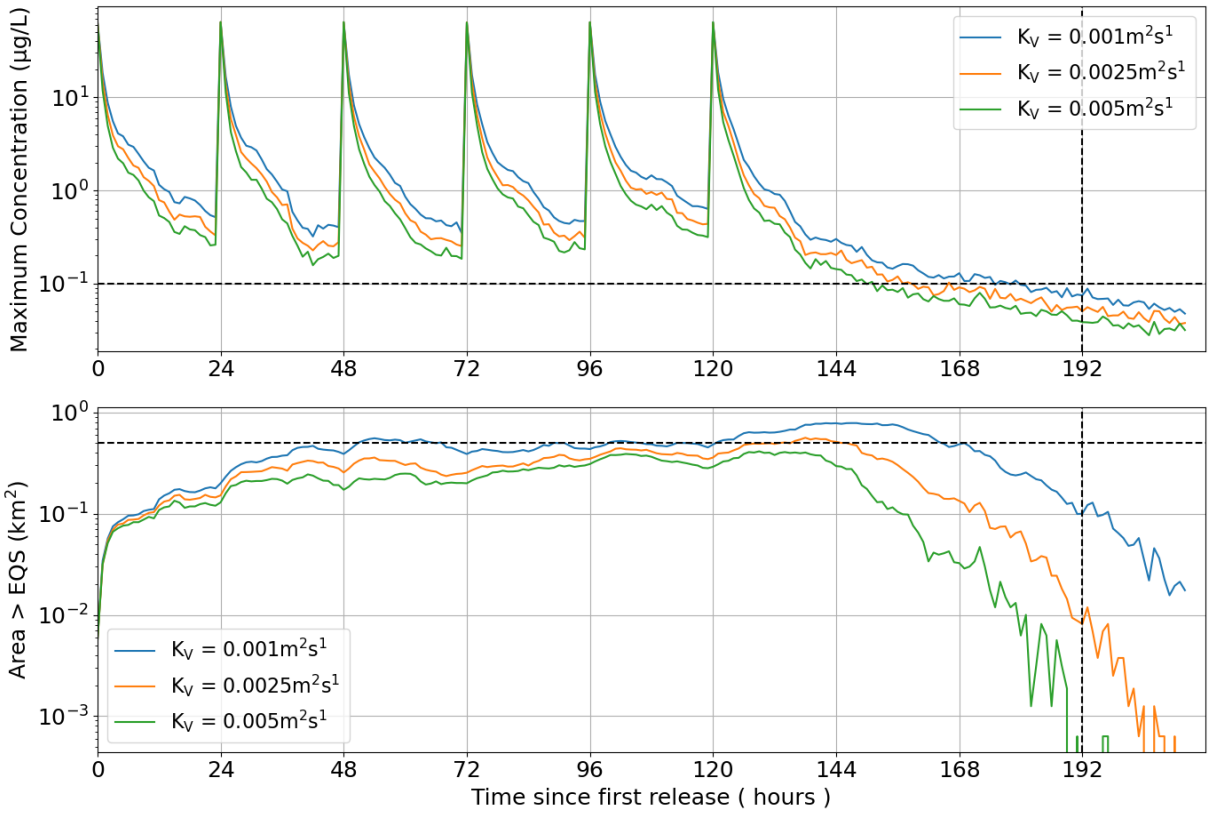

Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient K_V ($m^2\ s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.3 Sensitivity to Release Time

The baseline simulation was repeated with the time of the releases varied by up to ±6 hours, the purpose being to assess the influence, if any, of the state of the tide on subsequent dispersion. The results show some minor variability. A half-life of 134.4 hours was used in these runs which is thought to still be conservative.

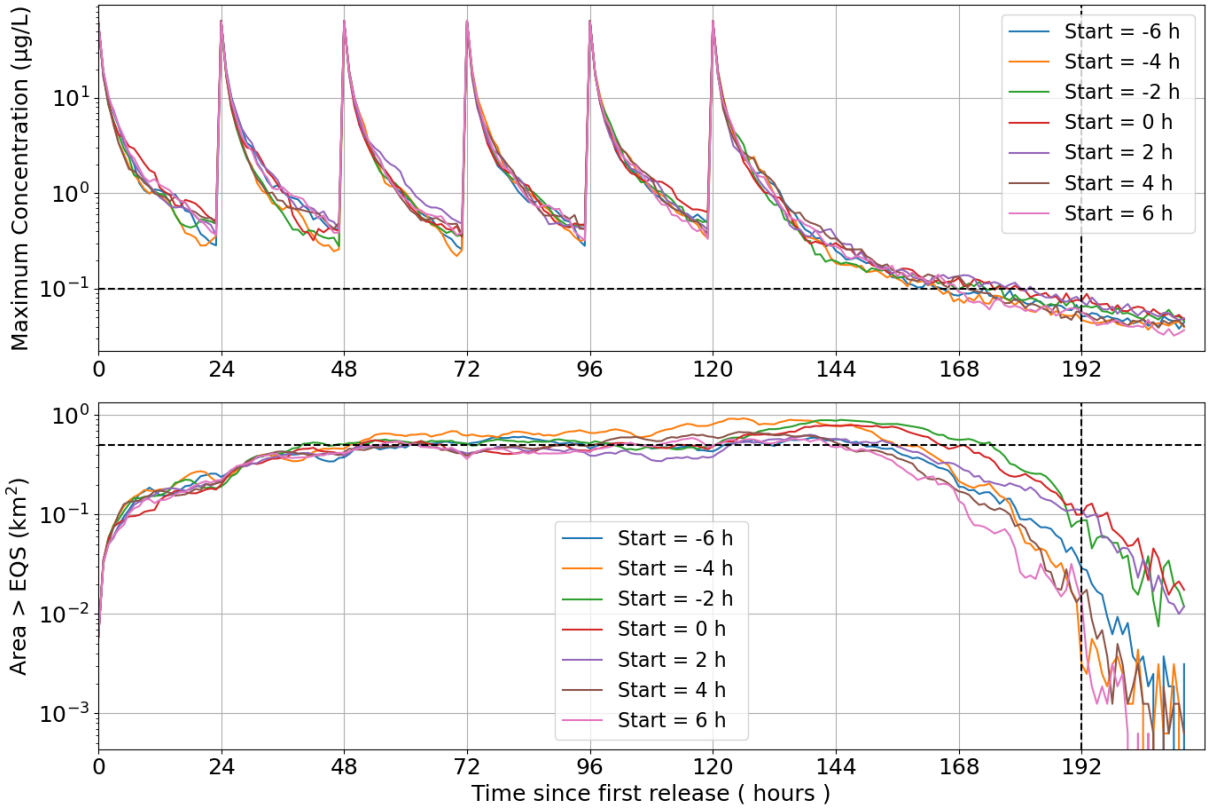

Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.4 Dispersion during Spring Tides, November 2016 (ID119)

Dispersion simulations were carried out during modelled spring tides in November 2016 (Figure 5), repeating the main set carried out for neap tides (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 652 g of azamethiphos. For all medicine half-lives, horizontal and vertical diffusion coefficients simulated both the MAC and area EQS were achieved (Figure 14).

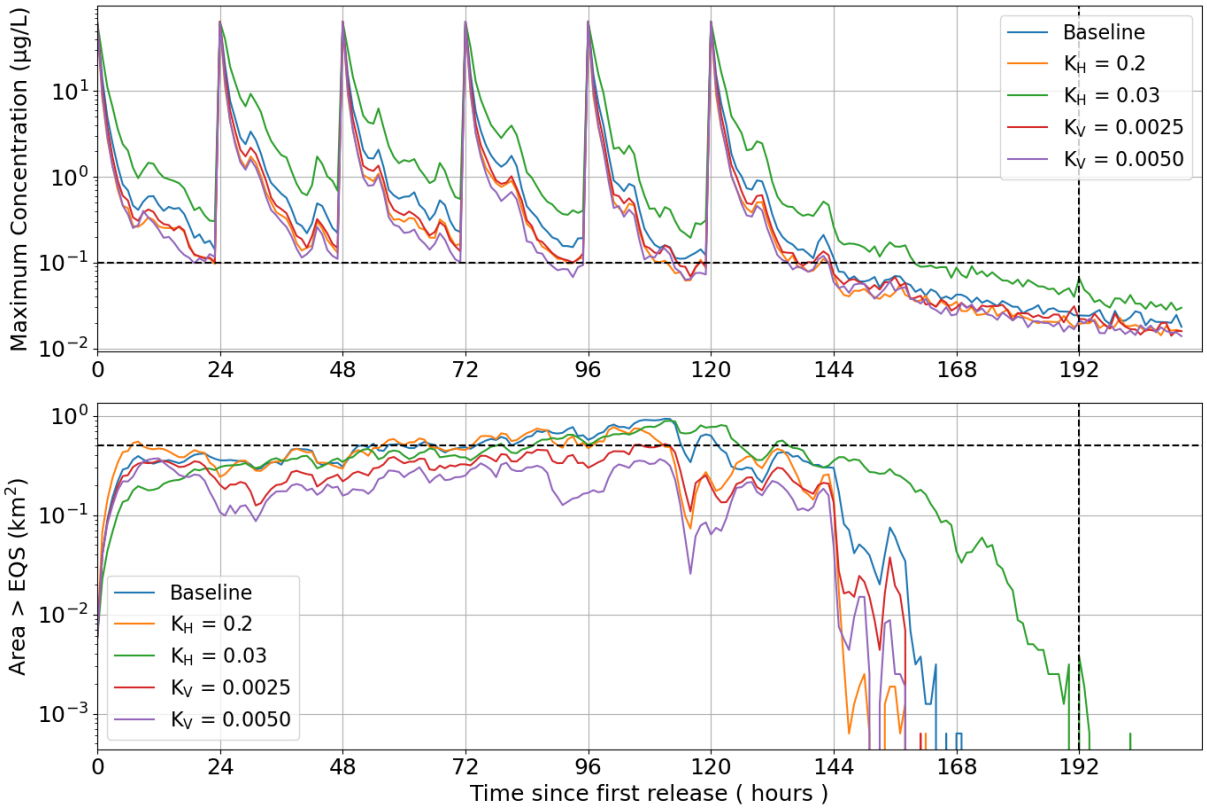

Figure 14. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient K_H ($m^2 s^{-1}$) and vertical diffusion coefficient K_V ($m^2 s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.5 Dispersion During Neap Tides, August - September 2017 (ID182)

A further set of dispersion simulations during modelled neap tides in August - September 2017 were carried out (Figure 15), repeating the main set carried out for neap tides in October 2016 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 652 g of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved. Some peaks in both concentration and area > EQS are observed and are assumed to be due to artefacts found in the model. But these quickly decrease back below the EQS in every case. The horizontal diffusion co-efficient used in these runs is also known to be highly conservative when looking at dispersion over time greater than an hour. These simulations demonstrate again that the modelled treatment regime will comfortably meet the EQS criteria.

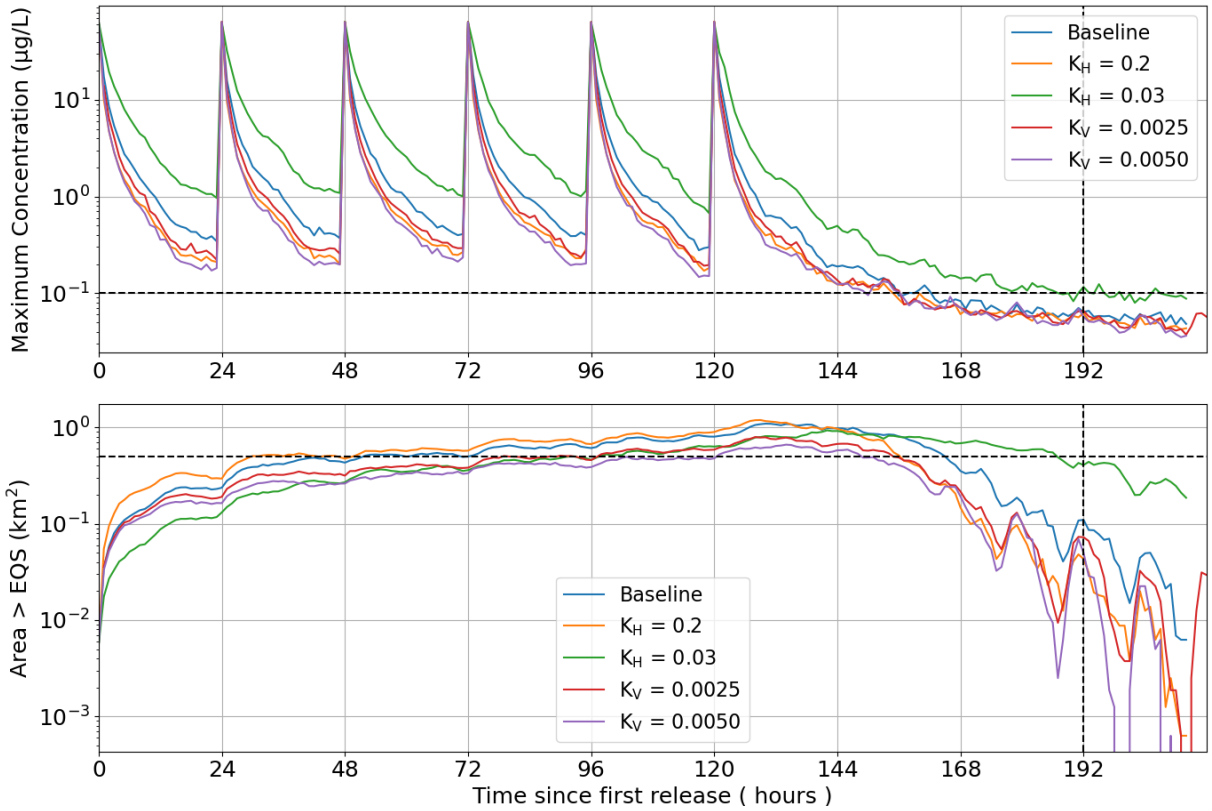

Figure 15. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, ninth and tenth set of model runs (Table 4). The model was run at neap tides from August - September 2017, horizontal diffusion coefficient K_H (m^2 s^{-1}) and vertical diffusion coefficient K_V (m^2 s^{-1}). The MAC and area limit 72 hours after the final treatment (Time = 192 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.6 3-Hour EQS

The 3-hour mixing zone is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 14.7 cm s^{-1} was used from ID119 (Table 1) which was thought to be a representative value for the surface 0 – 5 m layer at Carradale (South). The parameter values used in the calculation of the 3-hour mixing zone ellipse area are shown in Table 5.

The time series of the areas where the 3-hour EQS of 250 ng L^{-1} is exceeded for each individual pen treatment at neap tide (first release on 6th October 2016) are shown in . For each treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.222 km^2) after 3 hours. The peak concentration of 100 µg L^{-1} decreased to less than 10 µg L^{-1} within the 3-hour period.

For spring tide releases (first release on 12th November 2016), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 17). As for the neap tide simulation, the peak concentrations fell by an order of magnitude within the three hours.

This demonstrates that the discharge quantity of 652 g of azamethiphos from each of the six 160 m pens at Carradale (South) should not breach the 3-hour EQS.

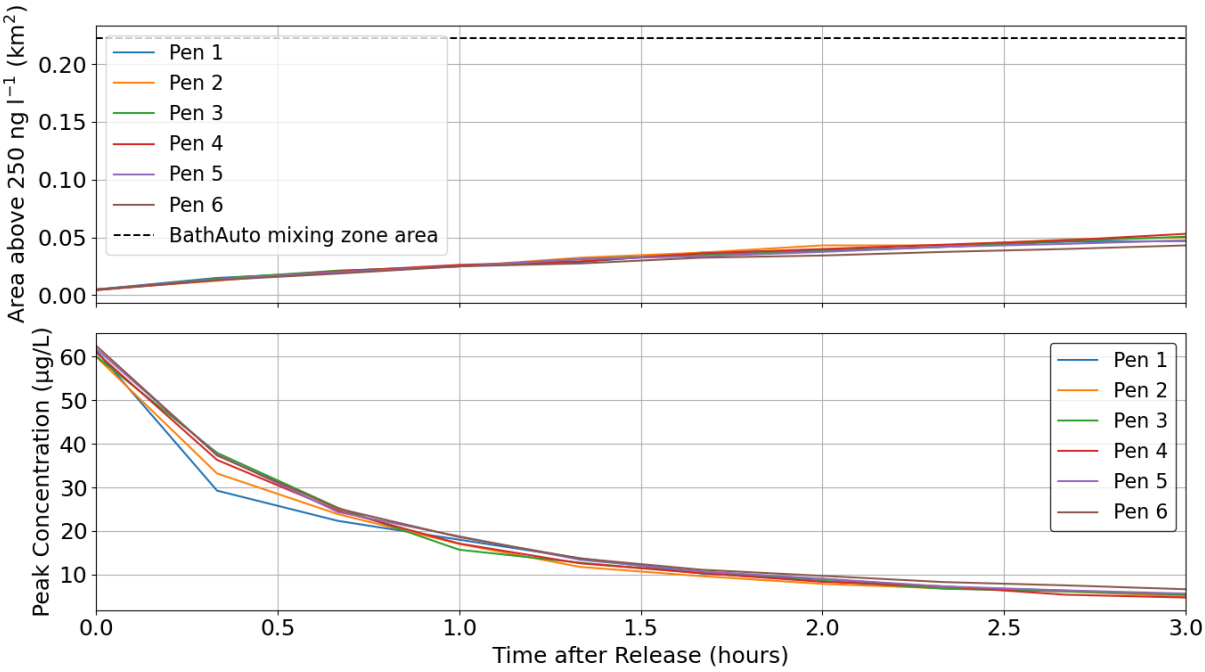

Figure 16. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

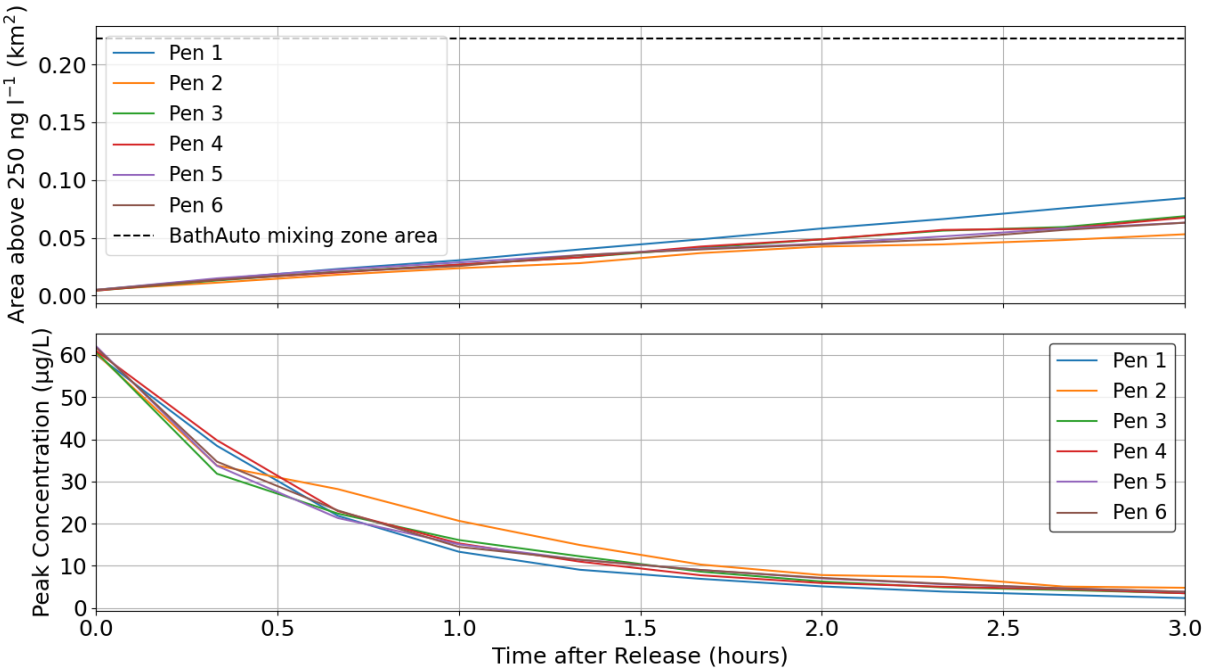

Figure 17. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area indicated (---).

3.7 Interactions with Special Features

Figure 18 shows the maximum peak concentrations of Azamethiphos every hour within the identified special feature area at spring tide for a 5 m layer above the seabed following treatment at Carradale (South). The concentrations shown during spring tide are minimal with maximum concentrations well below the 3-hour (0.25 µg L^{-1}) and the 72-hour (0.10 µg L^{-1}) MAC for the whole duration of the simulation.

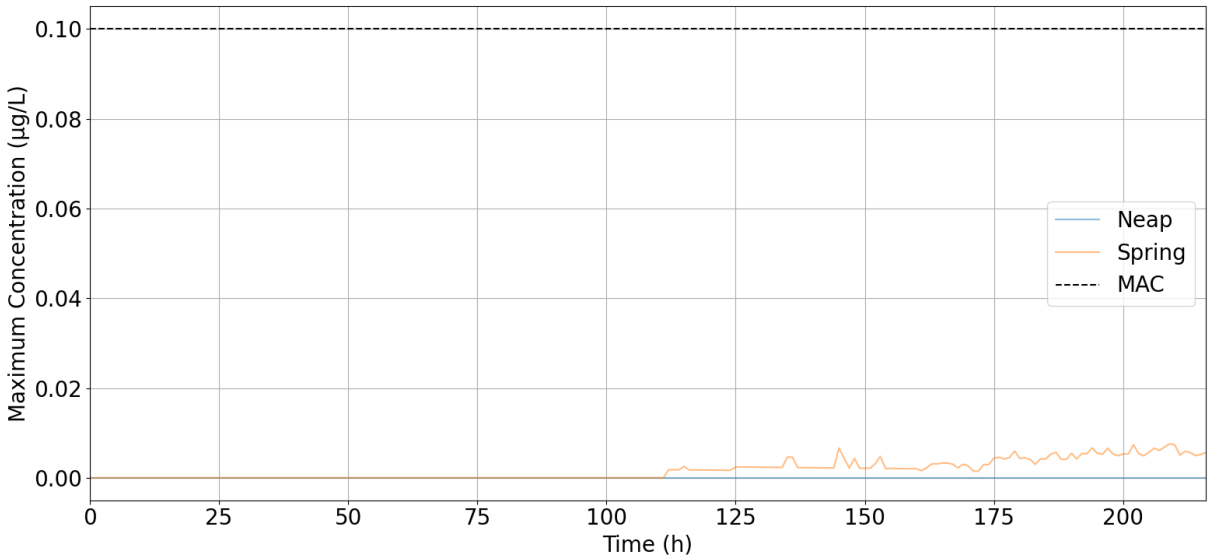

Figure 18. Maximum peak concentrations over neap and spring tides for South of Arran Marine Protected Area. The MAC at 72 hours of 0.1 µg L^{-1} is indicated by the horizontal dashed line.

4 SUMMARY AND CONCLUSIONS

A total of 21 dispersion simulations have been performed to assess whether bath treatments at Carradale (South) salmon farm will comply with pertinent EQS. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 652 g of azamethiphos for treatment, resulting in a total discharge over 5 days of 4.0 kg. Simulations were performed separately for modelled neap and spring tides, and the sensitivity of the results to key model parameters was tested. Results are summarised in Table 6.

Table 6. Summary of Results

Site Details	
Site Name:	Carradale South
Site Location:	Kilbrannan Sound
Peak Biomass (T):	2,500
Pen Details	
Number of Pens:	6
Pen Circumference (m):	160
Working Depth (m):	16
Pen Group Configuration:	2 x 3
Azamethiphos Consent	
Recommended 3-hour (g):	652
Recommended 24-hour (g):	652

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 652 g, should consistently comply with the EQS. The peak concentration during the baseline simulation after 192 hours (72 hours after the final treatment) was less than 0.1 µg L^{-1}, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg L^{-1} was substantially less than the allowable 0.5 km^2. In all simulations performed, including sensitivity testing, the EQS and MAC criteria were met, with the exception of the horizontal diffusivity runs (Run009 and Run019) with K_H=0.03. This diffusivity value is considered to be highly conservative over the period of an hour. Further simulations over a neap tide from later in 2017 demonstrated that the modelled treatment regime consistently complied with the relevant EQS and MAC with the exception of the horizontal diffusivity run with K_H=0.03. For the simulation during spring tides, greater dispersion meant that the MAC and EQS were met very comfortably. Peak concentrations near the seabed at the identified special feature area (SEPA, 2023) were found to be consistently less than the 3-hour and 72-hour MAC over the full treatment simulation. Therefore, it is believed that the requested daily quantity of 652 g of azamethiphos can be safely discharged at Carradale (South) without breaching the MAC or EQS.

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