Azamethiphos Dispersion Modelling
Isle of Rum, CAR/L/1152362

Mowi Scotland Limited

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Rum salmon farm will comply with pertinent environmental quality standards (EQS) . A realistic treatment regime, with 2 pen treatments per 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 2.46 kg and a total discharge over 4 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 2.46 kg of azamethiphos, should comfortably comply with the EQS. The peak concentration during the baseline simulation after 147 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 were performed to assess potential impacts of medicinal treatments on a nearby Priority Mean Feature (PMF). The simulations indicated that a small proportion of the surface water in the PMF area may briefly experience medicine concentrations above the 3-hour and 72-hour EQS. However, the PMF is a benthic feature (burrowed mud), and near-bed medicine concentrations were consistently zero through the simulations for both spring and neap tides.

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:	Rum
Site Location:	Isle of Rum
Peak Biomass (T):	3,300
Pen Details	
Number of Pens:	8
Pen Dimensions:	160m circumference
Working Depth (m):	15
Pen Group Configuration:	2 x 4
Azamethiphos	
Recommended 3hr Consent (kg):	1.23
Recommended 24hr Consent (kg):	2.46

1 INTRODUCTION

This report has been prepared by Mowi Scotland Ltd. to meet the requirements of the Scottish Environment Protection Agency (SEPA) for an application to use topical sealice veterinary medicines on a marine salmon farm at the Isle of Rum (Figure 1). The report presents results from coupled hydrodynamic and particle tracking modelling to describe the dispersion of bath treatments to determine EQS-compliant quantities for the proposed site biomass and equipment. The modelling procedure follows as far as possible guidance presented by SEPA in January 2022 (SEPA, 2022).

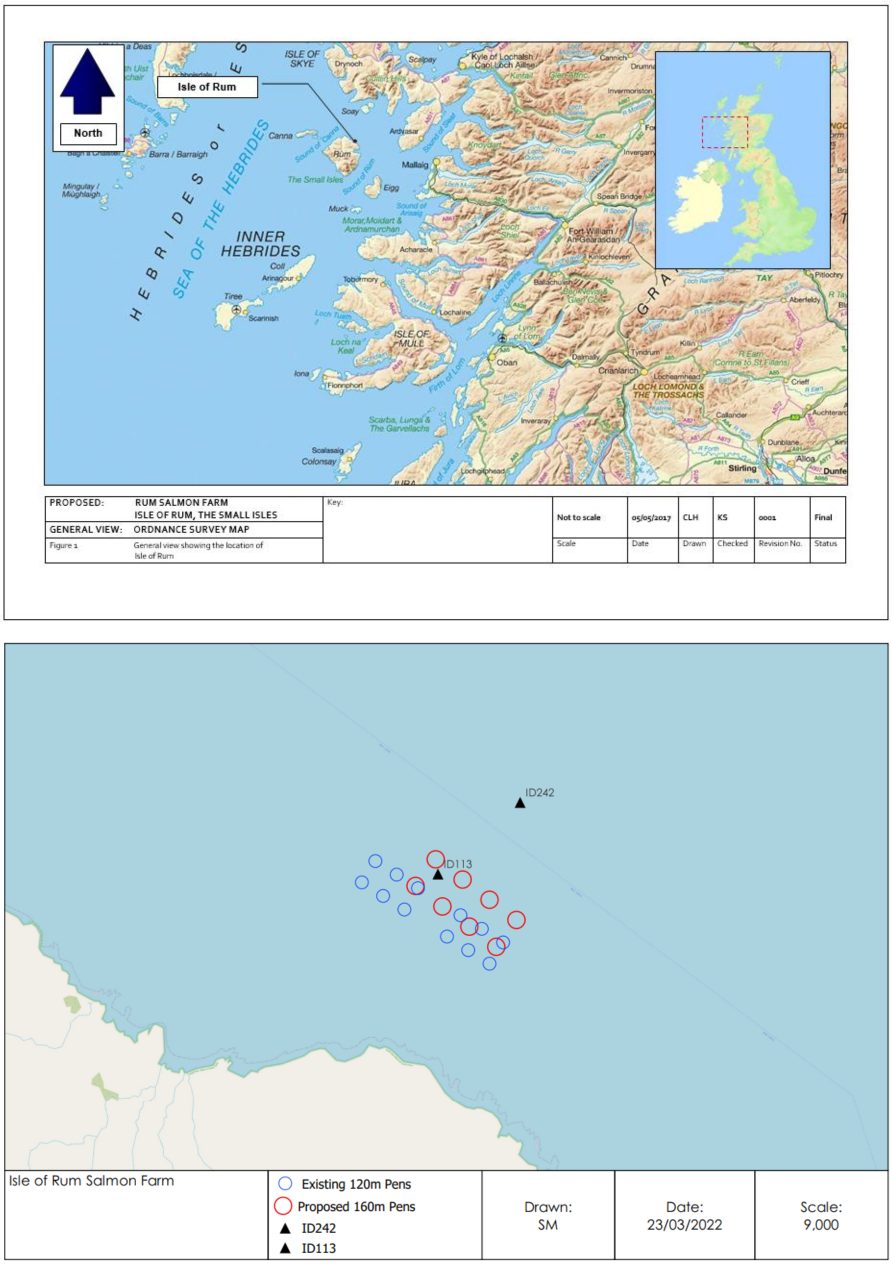

*Figure 1. Location of Rum salmon farm (top) and the location of the ADCP deployments (▲) relative to the proposed pen positions (**o**).*

1.1 Site Details

The site is situated off the north-east of the Isle of Rum (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:	Rum	
Site Location:	Isle of Rum	
Peak Biomass (T):	3,300	
Proposed Feed Load (T/yr)	8,431.5	
Proposed Treatment Use:	Azamethiphos	
Pen Details		
Group Location:	NG4108029	
Number of Pens:	8	
Pen Dimensions:	160m circumference	
Grid Matrix (m):	100	
Working Depth (m):	15	
Cone depth (m):	15	
Pen Group Configuration:	2 x 4	
Pen Group Orientation (°G):	133	
Pen Group Distance to Shore (km):	0.48	
Water Depth at Site (m):	40	
Hydrographic Data		
	ID113	**ID242**
Current Meter Position:	141101, 803023	141338, 803238
Depth at Deployment Position (m):	38.2	52.75
Surface Bin Centre Height Above Bed (m):	30.72	44.72
Middle Bin Centre Height Above Seabed (m):	19.72	32.72
Bottom Bin Centre Height Above Bed (m):	2.72	3.72
Duration of Record (days):	54.9	84.3
Start of Record:	15/08/2016	30/08/2018
End of Record:	09/10/2016	22/11/2018
Current Meter Averaging Interval (min):	20	20
Magnetic Correction to Grid North:	-3.99	-3.62
Bath Treatments		
3hr Recommended Consent Mass (kg):	1.23	
24hr Recommended Consent Mass (kg):	2.46	

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, Rum Hydrodynamic Model Description, June 2022), and is only summarised here.

For the hydrodynamics, the RiCOM model was used. RiCOM (River and Coastal Ocean Model) is a general-purpose hydrodynamics and transport model, which solves the standard Reynolds-averaged Navier-Stokes equation (RANS) and the incompressibility condition, applying the hydrostatic and Boussinesq approximations (Walters and Casulli, 1998). It has been tested on a variety of benchmarks against both analytical and experimental data sets. The model has been previously used to investigate the inundation risk from tsunamis and storm surge on the New Zealand coastline, the effects of mussel farms on current flows, and, more recently in Scotland to study tidal energy resource and the effects of energy extraction on the ambient environment (McIlvenny et al., 2016; Gillibrand et al., 2016b).

The mathematical equations are discretized on an unstructured grid of triangular elements which permits greater resolution of complex coastlines, such as typically found in Scotland. Therefore greater spatial resolution in near-shore areas can be achieved without excessive computational demand.

For the particle tracking component, Mowi's in-house model unptrack (Gillibrand, 2021) was used. The model used the hydrodynamic flow fields from the RiCOM model simulations. This model has been used previously to simulate sea lice dispersal (Gillibrand & Willis, 2007), the development of a harmful algal bloom (Gillibrand et al., 2016a) and the dispersion of cypermethrin from a fish farm (Willis et al., 2005). The approach for veterinary medicines is the same as for living organisms, except that medicine has no biological behaviour but instead undergoes chemical decay: the numerical particles in the model represent "droplets" of medicine of known mass, which reduces over time at a rate determined by a specified half-life. Particles are released at pen locations at specified times, according to a treatment schedule. The number of particles combined with their initial mass represents the mass of medicine required to treat a pen. The particles are then subject to advection, from the modelled flow fields, horizontal and vertical diffusion, and chemical decay. Concentrations of medicine can be calculated throughout the simulation and compared with relevant Environmental Quality Standards (EQS) e.g. 72 hours after the final treatment. Here, we have modelled the dispersion of azamethiphos following a treatment scenario at Rum 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 East Coast of Lewis and Harris (ECLH) sub-model mesh of the Scottish Shelf Model (SSM; MS, 2016) (Figure 2). Model resolution was enhanced in the Small Isles region particularly around the Mowi site at Rum

(Figure 3). The spatial resolution of the model varied from 25m in some inshore waters to 5km along the open boundary. The model consisted of 75,331 nodes and 142,263 triangular elements. Bathymetry was taken from the European Marine Observation and Data Network (EMODnet). 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 cages. The bathymetry in the original EMODnet model is acceptable in the Cuillin Sound area where the model is focussed (Figure 4).

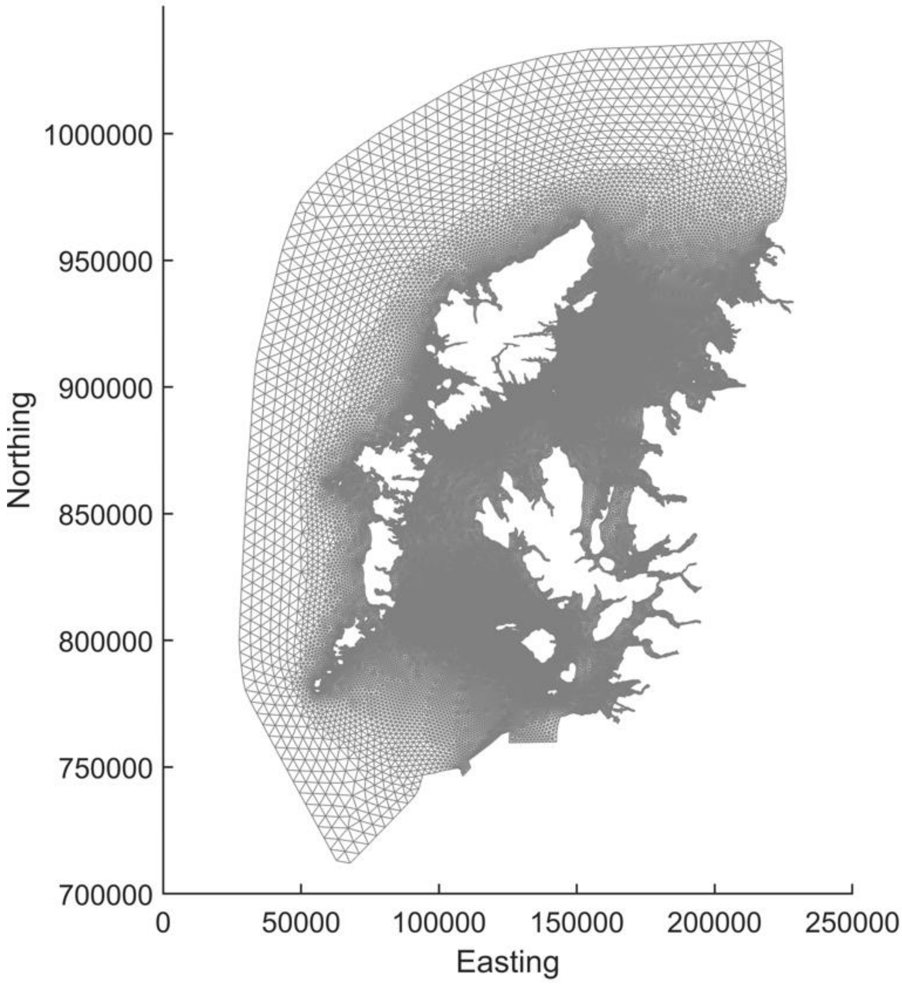

Figure 2. The mesh and domain of the modelling study, adapted from the ECLH sub-model.

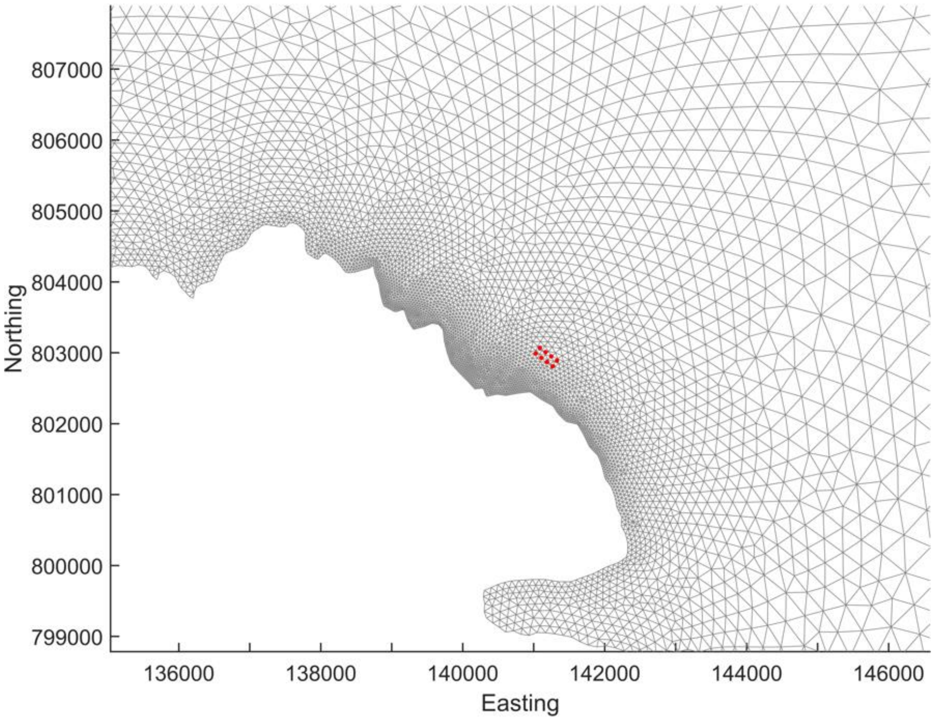

Figure 3. The unstructured mesh around the Rum site in the modified model grid, with the proposed pen locations indicated (o).

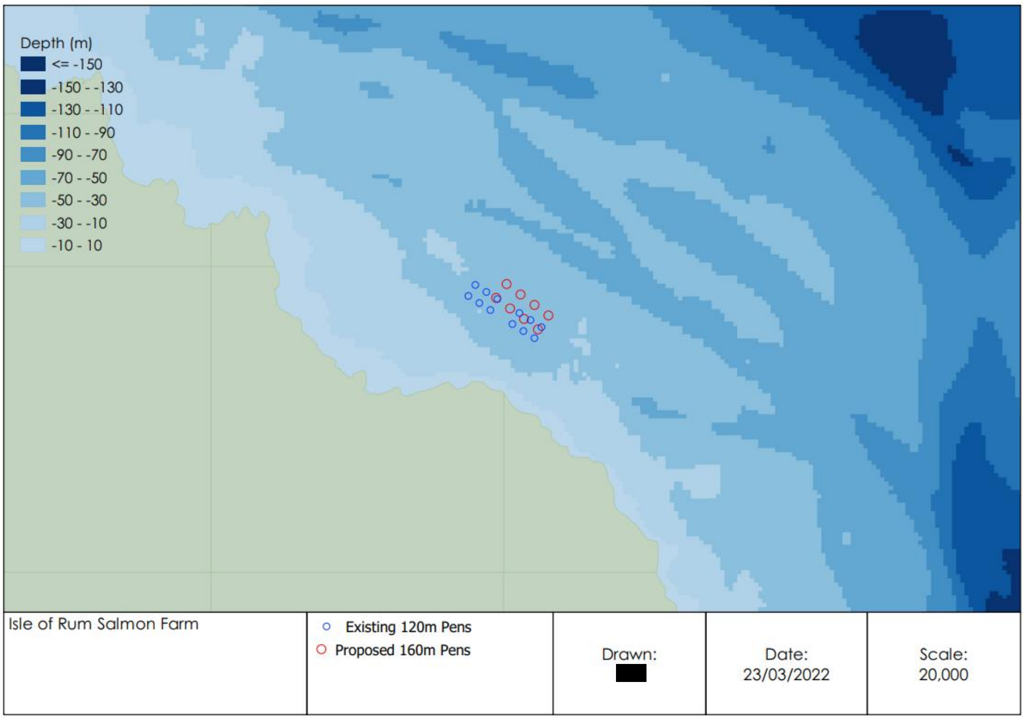

Figure 4. Localised bathymetry (m) around Rum from the modified model.

The model is forced at the outer boundaries by 8 tidal constituents (M_2, S_2, N_2, K_2, O_1, K_1, P_1 and Q_1) 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 Hydrodynamic Model Description (Mowi Scotland Ltd, Rum Hydrodynamic Model Description, 2022).

2.3 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the unptrack model (Gillibrand, 2021), simulates the dispersion of patches of medicine discharged from pens following treatment using tarpaulins. The unptrack model uses the same unstructured mesh as the hydrodynamic model, and reads the flow fields directly from the hydrodynamic model output files. Therefore, no spatial or temporal interpolation of the current fields is required, although current velocities are interpolated to particle locations within unptrack. The treatment scenario assumed 2 pens can be treated per day.

To simulate the worst-case scenario, the dispersion modelling was initially conducted using flow fields over a period of 7 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^{-1}, 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. 980552* numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation ran for a total of 172 hours (7.16 days). This covered the treatment period (75 hours), a dispersion period to the EQS assessment after 147 hours (72 hours after the final treatment), and an extra 25 hours to check for chance concentration peaks. At every hour of the simulation, particle locations and properties (including the decaying mass) were stored and subsequently concentrations calculated. Concentrations were calculated on a grid of 25m x 25m squares using the same depth range as the treatment depth (i.e. 0 – 5 m). Using a regular grid for counting makes calculating particle concentrations and presenting the results easier.

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

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

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

Sensitivity analyses were conducted to assess the effects of:

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

The dispersion simulations were performed separately over neap and spring tides during 2016 (ID113) (Figure 5). A further set of simulations was performed over neap tides in 2018 (ID242) to confirm the adequacy of dispersion during the weakest tides (Figure 6).

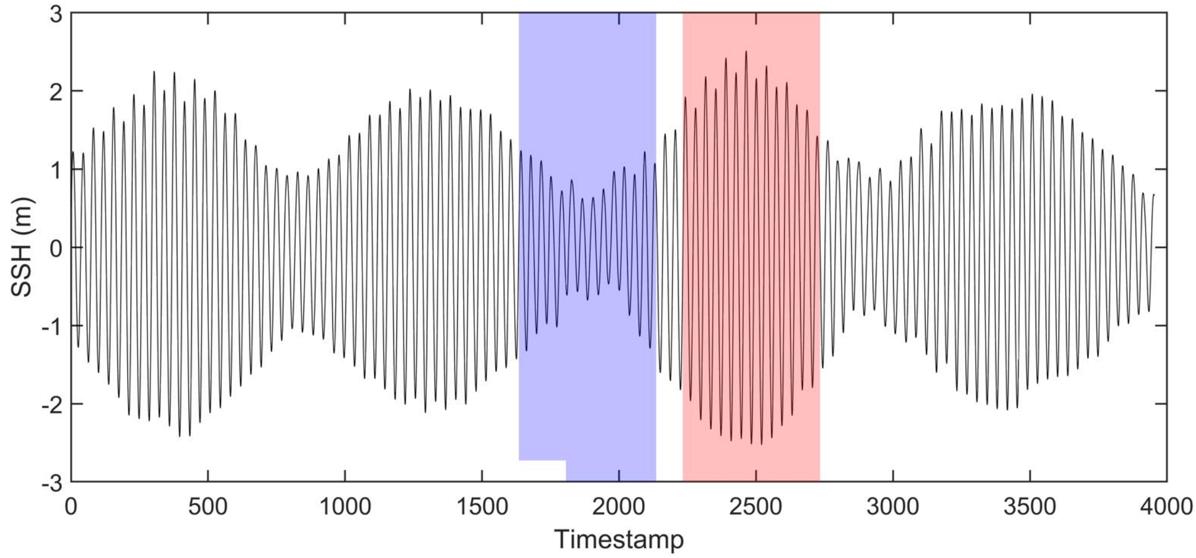

Figure 5. Sea surface height (SSH) at Rum from 15th August –9th October 2016 (ID113). Dispersion simulations were performed over periods of neap tides (blue, start day 8th September 2016) and spring tides (red, start day 15th September 2016)

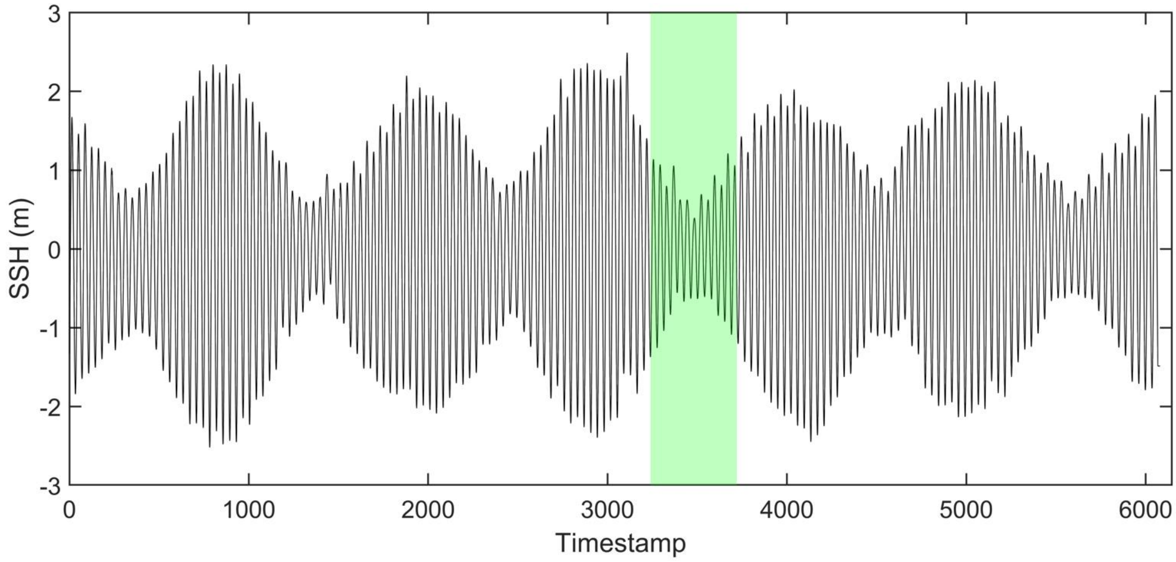

Figure 6. Sea surface height (SSH) at Rum from 30th August 2018 – 21st December 2018 (ID242). Dispersion simulations were performed over periods of neap tides (green, start day 14th October 2018).

2.4 Medicine Dispersion Simulations

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

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

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

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (kg)	Release Time (hr)
1	141087	803069	5	1.23	0
2	141027	802990	5	1.23	3
3	141167	803009	5	1.23	24
4	141107	802929	5	1.23	27
5	141247	802949	5	1.23	48
6	141187	802869	5	1.23	51
7	141327	802889	5	1.23	72
8	141267	802809	5	1.23	75

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

Set	Run No.	T 1/2 (h)	Kh	Kv	Start Time
Neap Tides, Start day = 24 (8th September 2016, ID113)					
Baseline	1	134.4	0.1	0.001	00:00
1	2	134.4	0.1	0.001	00:00 -6h
	3	134.4	0.1	0.001	00:00 -4h
	4	134.4	0.1	0.001	00:00 -2h
	5	134.4	0.1	0.001	00:00 +2h
	6	134.4	0.1	0.001	00:00 +4h
	7	134.4	0.1	0.001	00:00 +6h
2	8	213.6	0.1	0.001	00:00
	9	55.2	0.1	0.001	00:00
3	10	134.4	0.2	0.001	00:00
	11	134.4	0.03	0.001	00:00
4	12	134.4	0.1	0.0025	00:00
	13	134.4	0.1	0.005	00:00
Spring Tides, Start day = 31 (15th September 2016, ID113)					
5	14	134.4	0.1	0.001	00:00
	15	213.6	0.1	0.001	00:00
	16	55.2	0.1	0.001	00:00
6	17	134.4	0.2	0.001	00:00
	18	134.4	0.03	0.001	00:00
7	19	134.4	0.1	0.0025	00:00
	20	134.4	0.1	0.005	00:00
Neap Tides, Start day = 44 (14th October 2018, ID242)					
8	21	134.4	0.1	0.001	00:00
	22	213.6	0.1	0.001	00:00
	23	55.2	0.1	0.001	00:00
9	24	134.4	0.2	0.001	00:00
	25	134.4	0.03	0.001	00:00
10	26	134.4	0.1	0.0025	00:00
	27	134.4	0.1	0.005	00:00

2.5 Interaction with Sensitive Features

A near-by feature of interest has been identified (SEPA 2022) which is at potential risk from medicine influence and hence must be considered when modelling the treatment releases from Rum. Table 5 shows details of the feature of interest, and its location is indicated in Figure 7.

Table 5. Details of Identified Feature

Feature name	Feature Type	Location	Reason for Identification
Burrowed Mud	PMF Habitat	(See Figure 7)	Medicine Influence

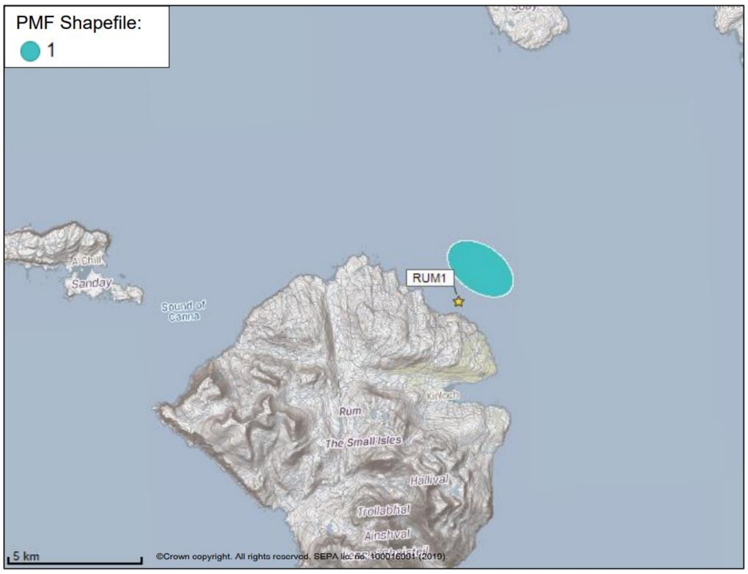

Figure 7. Burrowed Mud PMF location near the Isle of Rum Salmon Farm (SEPA, 2022)

Predicted concentrations of azamethiphos within the PMF area 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 made for near-surface waters and, since the PMF is a benthic habitat, for a 5 m thick layer immediately above the seabed.

2.6 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 11.9 cm s^{-1} was used from ID113 (Table 6) which was the current meter deployment closest to the site location and most representative of the currents at the site.

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.

Table 6. 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})	0.119
Area of 160m pen (km^2)	0.002037
Distance from shore (km)	0.485
Mean water depth (m)	38.2
Treatment Depth (m)	5
Mixing zone ellipse area (km^2)	**0.1879649**

2.7 Cumulative Modelling

As well as sensitivity analysis, cumulative bath modelling was also undertaken for Rum and near-by site, Muck, to check for any interaction between treatments. A proposed organic site by the Isle of Canna was not included in the cumulative modelling because no azamethiphos consent would be being applied for. Table 7 shows details of the two sites used in the cumulative model runs. Because an application has already been submitted by Mowi Scotland to modify the Muck site to 8 x 160m circumference pens and increase the Azamethiphos consent, the cumulative modelling runs used the proposed new layout and proposed medicine consent to ensure maximum possible discharges were simulated.

Table 7. Details of sites included in cumulative modelling

	Rum	Muck
Company:	Mowi	Mowi
Site location:	NG 4086 0300	NM 4304 8056
Peak biomass (T):	3,300	4,069
No. of pens:	8	8
Pen dimensions:	160m circumference	160m circumference
Pen configuration:	2 x 4	2 x 4

A treatment depth of 5 m was chosen as a realistic net depth during application of the medicine for the 160m circumference pens at Muck. Table 8 shows the total treatment mass used at each site. A total mass of 18 kg of azamethiphos was released from the cumulative modelling simulations. At Rum, 2 pens were treated per day at a dosage of 120 µg L^{-1}, following the treatment schedule from the sensitivity runs. The initial mass released per pen was set as the 3hr limit which is being applied for, 1.23 kg. The EQS was then applied, as before, 72 hours after the final treatments.

Dispersion simulations were performed over neap and spring tides from August - October 2016 (Figure 5, ID113) with parameters matching that of the baseline run performed for Rum only. The pen locations and medicine release times are listed in Table 9.

Table 8. Total mass of azamethiphos released from sites during the cumulative modelling simulations

Site	24 hr mass released (kg)	Total mass released (kg)
Rum	2.46	9.84
Muck	1.02	8.16

The start time of the treatments were adjusted accordingly to allow for both sites to complete treatment at the same time on the same day so that the EQS could be applied. The simulations ran for 265 hours. This covered the treatment period (168 hours), a dispersion period to the EQS assessment after 240 hours (72 hours after the final treatment), and an extra 25 hours to check for chance concentration peaks, as done previously. The simulation used ~ 1.8 million numerical particles in total, each particle representing 10 mg of azamethiphos.

Table 9. Pen locations and treatment schedule for the cumulative modelling runs.

Pen	Site	Easting	Northing	Treatment Mass (kg)	Release Time Schedule (h)
1	Rum	141087	803069	1.23	93
2	Rum	141027	802990	1.23	96
3	Rum	141167	803009	1.23	117
4	Rum	141107	802929	1.23	120
5	Rum	141247	802949	1.23	141
6	Rum	141187	802869	1.23	144
7	Rum	141327	802889	1.23	165
8	Rum	141267	802809	1.23	168
1	Muck	143200	780207	1.02	0
2	Muck	143295	780238	1.02	24
3	Muck	143169	780302	1.02	48
4	Muck	143264	780333	1.02	72
5	Muck	143138	780397	1.02	96
6	Muck	143233	780428	1.02	120
7	Muck	143107	780492	1.02	144
8	Muck	143202	780525	1.02	168

2.8 Diffusion Coefficients

Selection of the horizontal diffusion parameter, K_H, was guided by dye releases conducted at the near-by Muck site by Anderson Marine Surveys Ltd on 20th September 2017, along with several other dye release studies undertaken at other salmon farm locations. Dye tracking studies proceed by releasing a known quantity of dye into the sea, and then attempting to map the resulting dye patch as it disperses over time by deploying a submersible fluorometer from a boat. Each survey of the patch takes a finite amount of time (typically less than 30 minutes) and is usually made up of several transects which attempt to criss-cross the patch. An estimate of horizontal diffusivity can be made from each transect, but the location of the transect relative to the centre of the patch (and the highest concentrations) is often uncertain. The estimates of horizontal diffusivity shown in Figure 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 Muck 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.

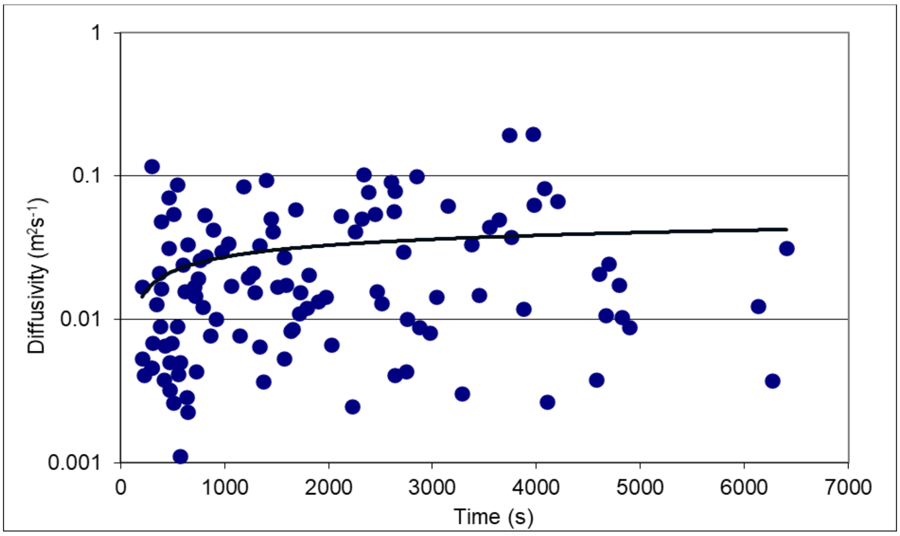

Figure 8. Estimated horizontal diffusivity ($m^2\ s^{-1}$) from dye release experiments at Muck on 20th September 2017. The mean diffusivity was 0.03 $m^2\ s^{-1}$.

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

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

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. 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 = 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.

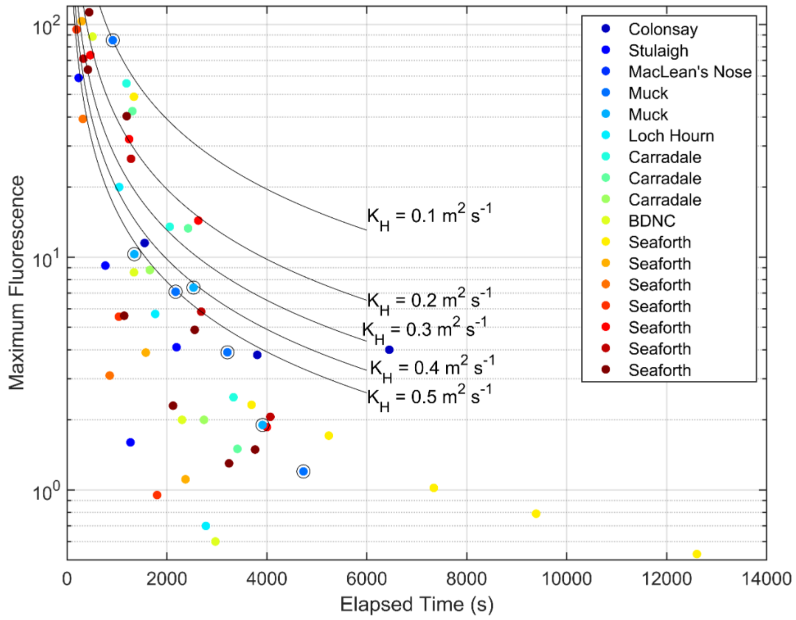

Figure 9. Maximum fluorescence measured following dye releases at a number of Mowi sites in Scotland. The data points from Muck are circled. The black lines indicate the rate at which the maximum concentration would fall at different horizontal diffusivities.

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

Most of the simulations described here were conducted using a value of K_H = 0.1 $m^2\ s^{-1}$, the minimum horizontal diffusion given for modelling bath treatments over periods greater than half-an-hour. However, the sensitivity of the model to K_H was explored.

3 RESULTS

3.1 Dispersion During Neap Tides, September 2016 (ID113)

A standard treatment of 8 x 160m pens, with a reduced net depth of 5 m and assuming 2 pens could be treated per day, 3 hours apart, 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 2.46 kg and a total treatment release of 9.84 kg over 75 hours. The dispersion of the medicine during and following treatment from Run001 (Table 4) is illustrated in Figure 10. After 27 hours, as the second treatment on Day 2 was discharged, discrete patches of medicine are evident from the first pair of treatment releases from the first day, which have merged, and the first treatment on Day 2. The maximum concentration at this time was about 120 µg/L, due to the release of the fourth treatment. After 51 hours, as the treatment was discharged, discrete patches of medicine from the previous treatment releases are still evident, but the patches of medicine have rapidly dispersed and are already down to concentrations of the same order as the EQS (0.04 µg/L). The maximum concentration at this time was again about 120 µg/L, due to the release of the sixth treatment.

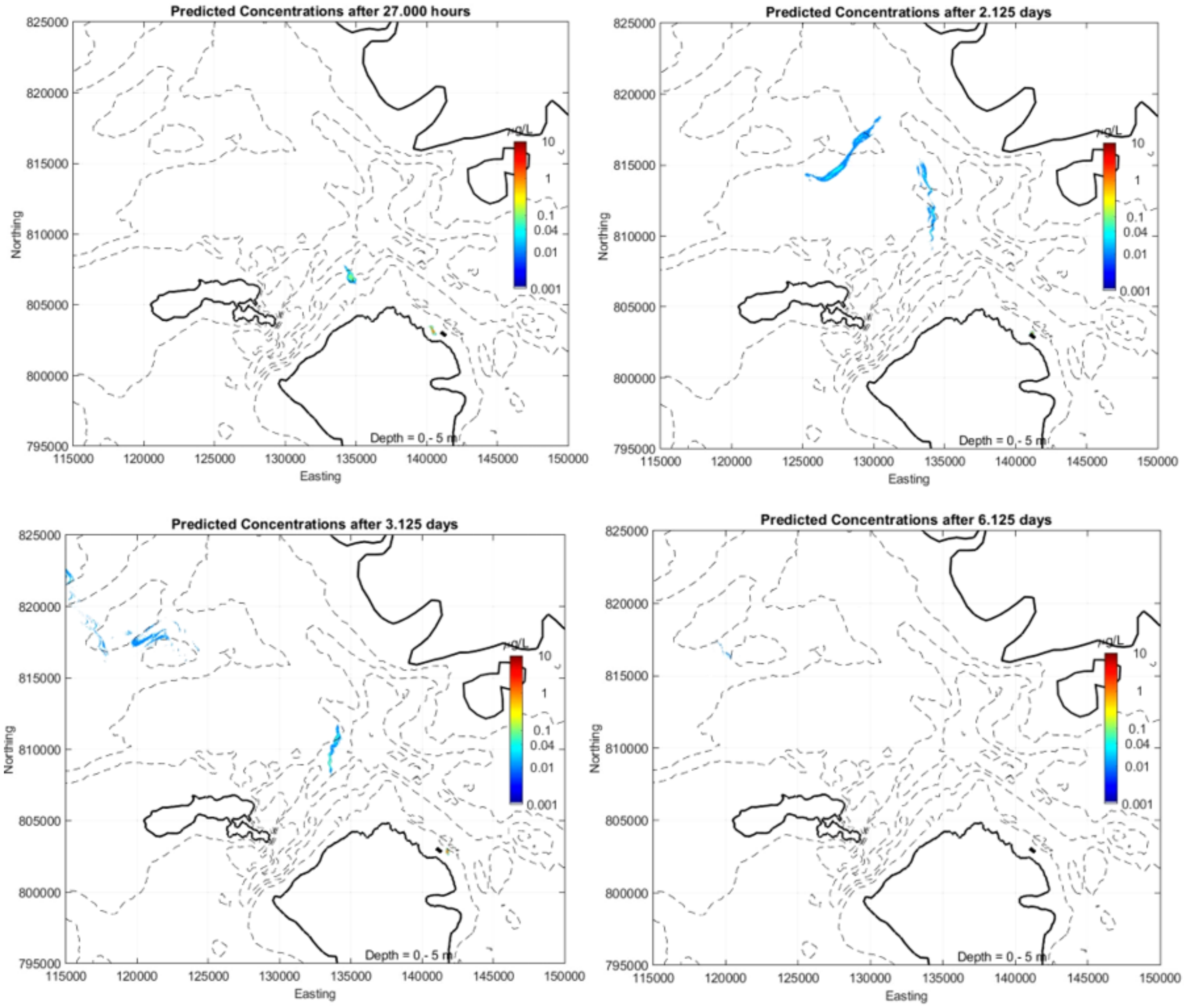

Figure 10. Predicted concentration fields for a dispersion simulation at neap tides after 27 hours (top left), 51 hours (top right), 75 hours (bottom left) and 147 hours (bottom right).

The treatment schedule completed after 75 hours (3.125 days). At this stage, the medicine released on earlier days had already dispersed north-west. It is noticeable that dispersion of the medicine does not happen in a gradual “diffusive” manner, but is largely driven by eddies and horizontal shear in the spatially-varying velocity field, which stretches and distorts the medicine patches and enhances dispersion. Following the final treatment at 75 hours, the treatment patches were rapidly dispersed and concentrations rapidly fell away below the EQS. Remnants of medicine are seen in the Cuillin Sound but at concentrations below the MAC.

The time series of maximum concentration from this simulation is shown in Figure 11. The 8 peaks in concentration of ~120 µg/L following each treatment event over the first 4 days are evident. Following the final treatment after 75 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 = 147 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 1.5 km^2 during treatment on Day 2, but had fallen below 0.5 km^2 within 36h of the final treatment; by 72h after the final treatment, the exceeded area was close to zero (Figure 10 and 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 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.

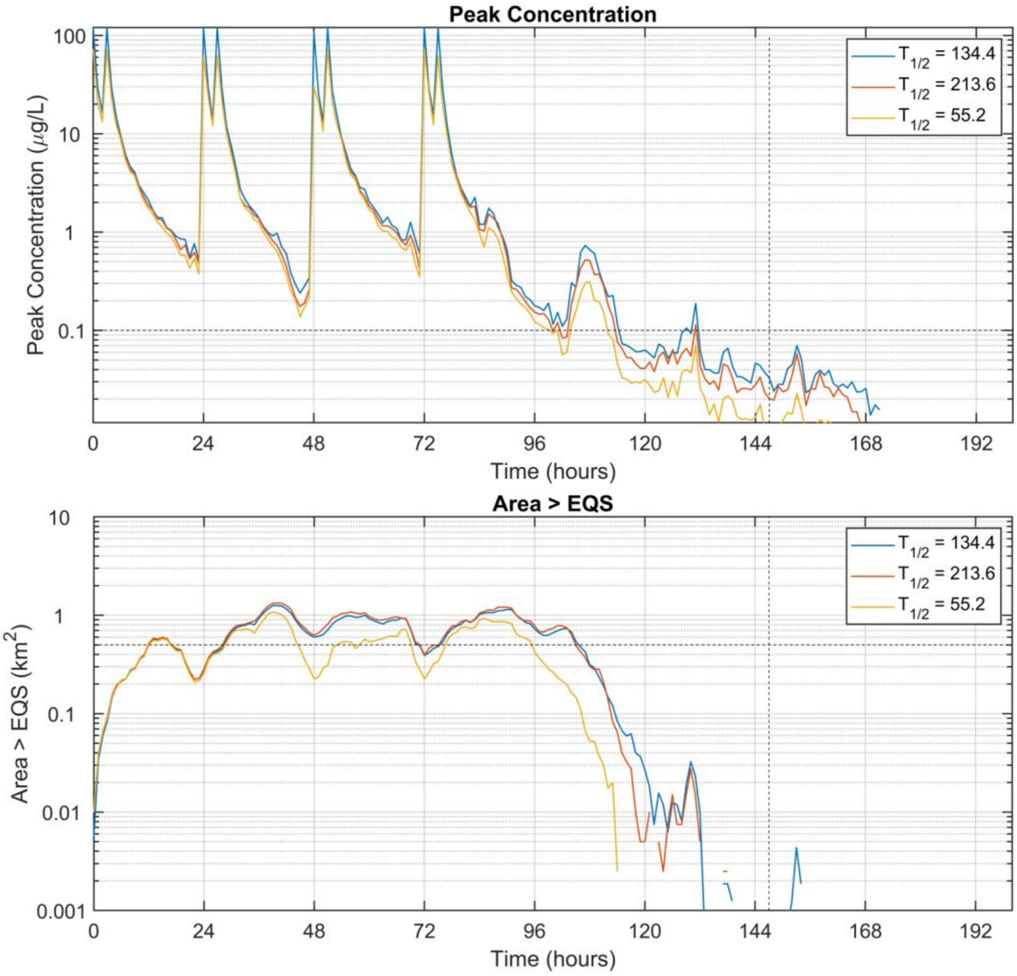

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tide with varying medicine half-life ($T_{1/2}$). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of 0.1 µg/L and 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 1.5 km^2 following treatment on Day 2, 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 = 0.1 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 12. The time series confirm that the MAC was not exceeded after 147 hours (72 hours after the final treatment) with any of the different horizontal diffusion coefficients. The area limit of 0.5 km^2 was also comfortably met in all cases.

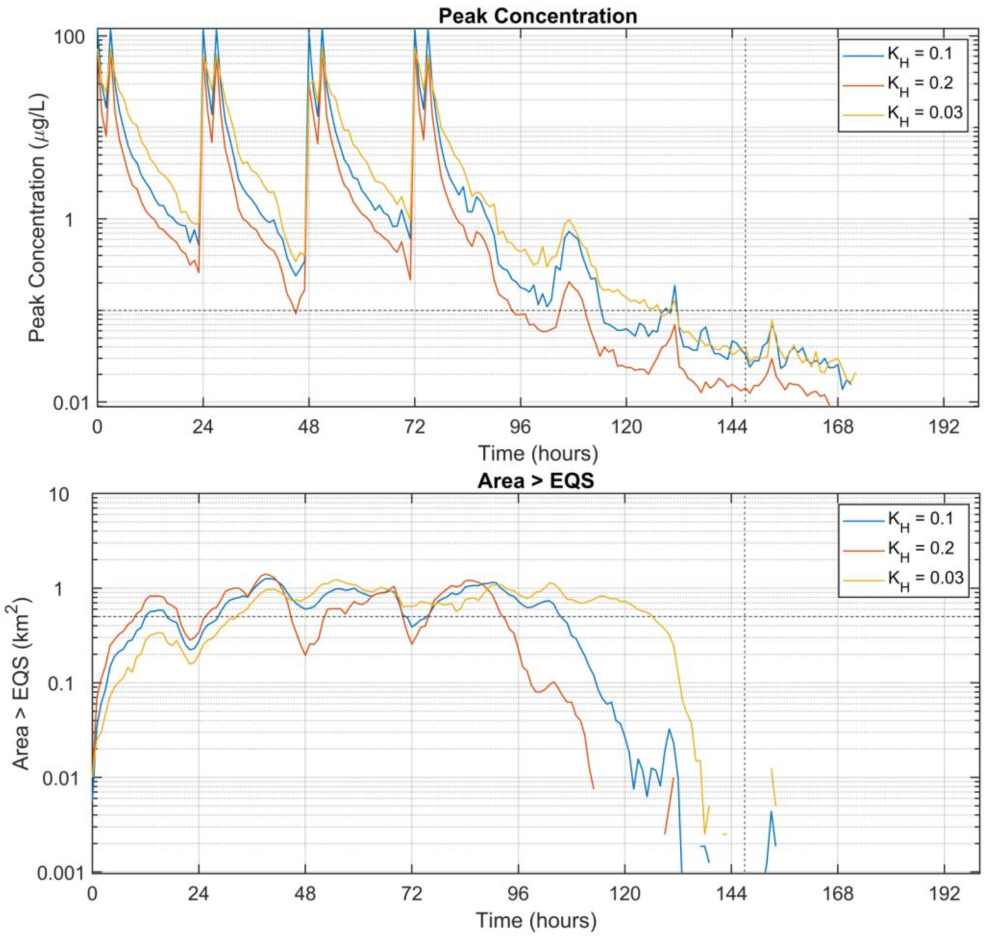

Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient K_H (m^2 s^{-1}). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

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 smaller areas where the EQS was exceeded.

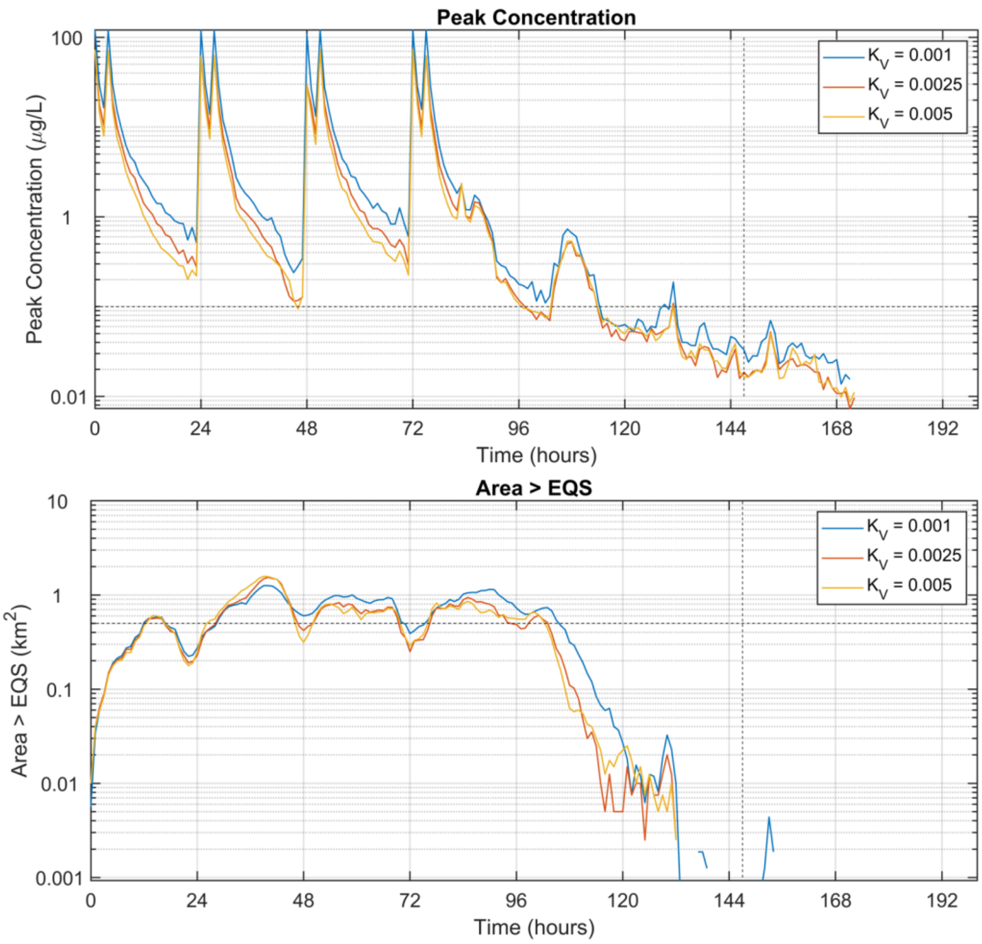

Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient K_V (m^2 s^{-1}). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.4 Sensitivity to Release Time

The baseline simulation was repeated with the time of the releases varied by up to ±6 hours, the purpose being to assess the influence, if any, of the state of the tide on subsequent dispersion. The results show some variability including some small concentration peaks which are potentially down to an artefact in the model (Figure 14). However, this only causes a very minor MAC breach for +6hrs. A half-life of 134.4 hours was used in these runs which is thought to still be conservative.

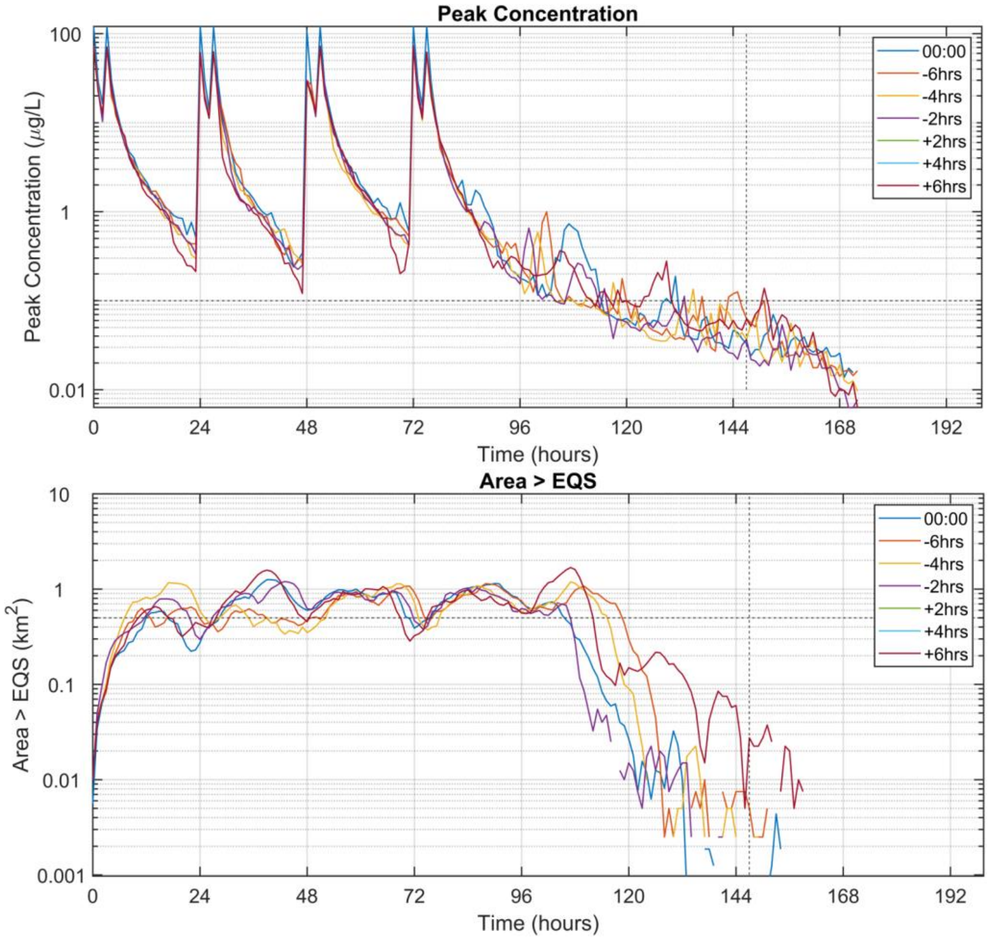

Figure 14. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of 0.1 µg/L and 0.5 km² are indicated by the horizontal dashed lines.

3.5 Dispersion during Spring Tides, September 2016 (ID113)

Dispersion simulations were carried out during modelled spring tides in September 2016 (Figure 5), repeating the main set carried out for neap tides (Table 4). The same treatment scenario of 2 treatments per day, 3 hours apart, 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 achieved (Figure 15).

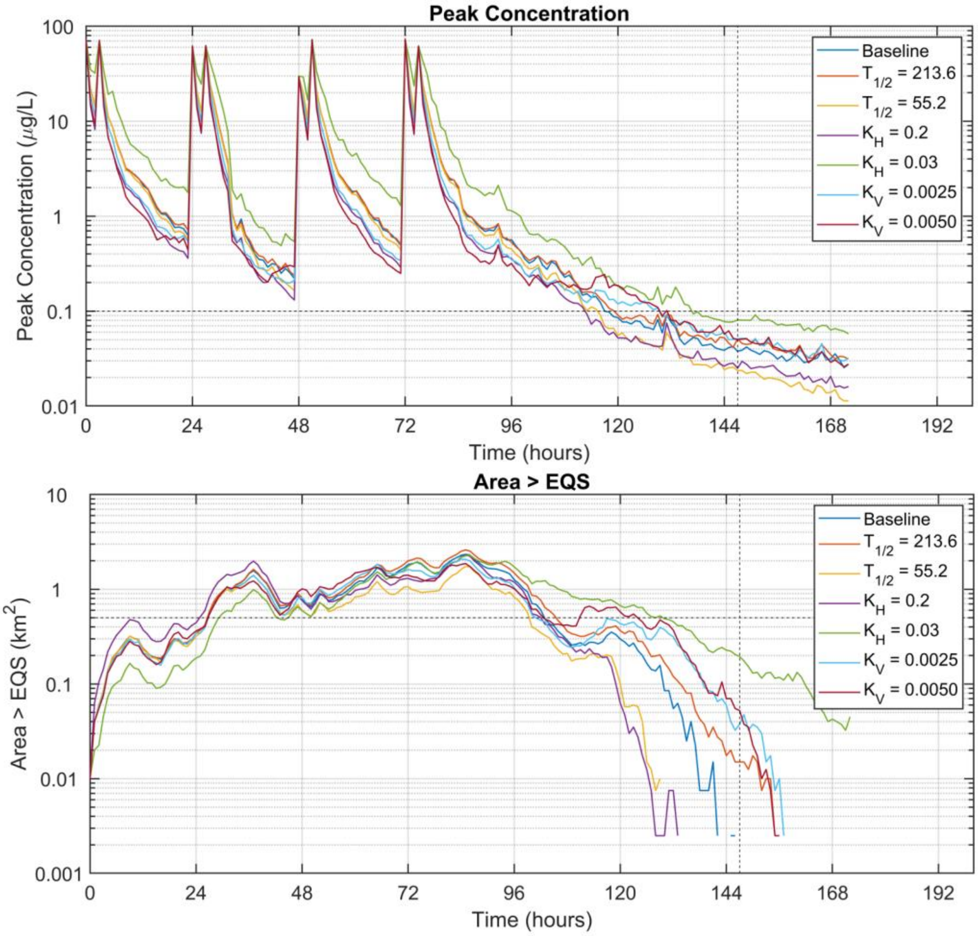

Figure 15. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient K_H ($m^2 s^{-2}$) and vertical diffusion coefficient K_V ($m^2 s^{-2}$). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.6 Dispersion During Neap Tides, October 2018 (ID242)

A further set of dispersion simulations during modelled neap tides in October 2018 were carried out (Figure 6), repeating the main set carried out for neap tides in September 2016 (Table 4). The same treatment scenario of 2 treatments per day, 3 hours a part, 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, apart from a minor failure seen with K_H = 0.03 (Figure 16). However, this horizontal diffusion co-efficient is 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.

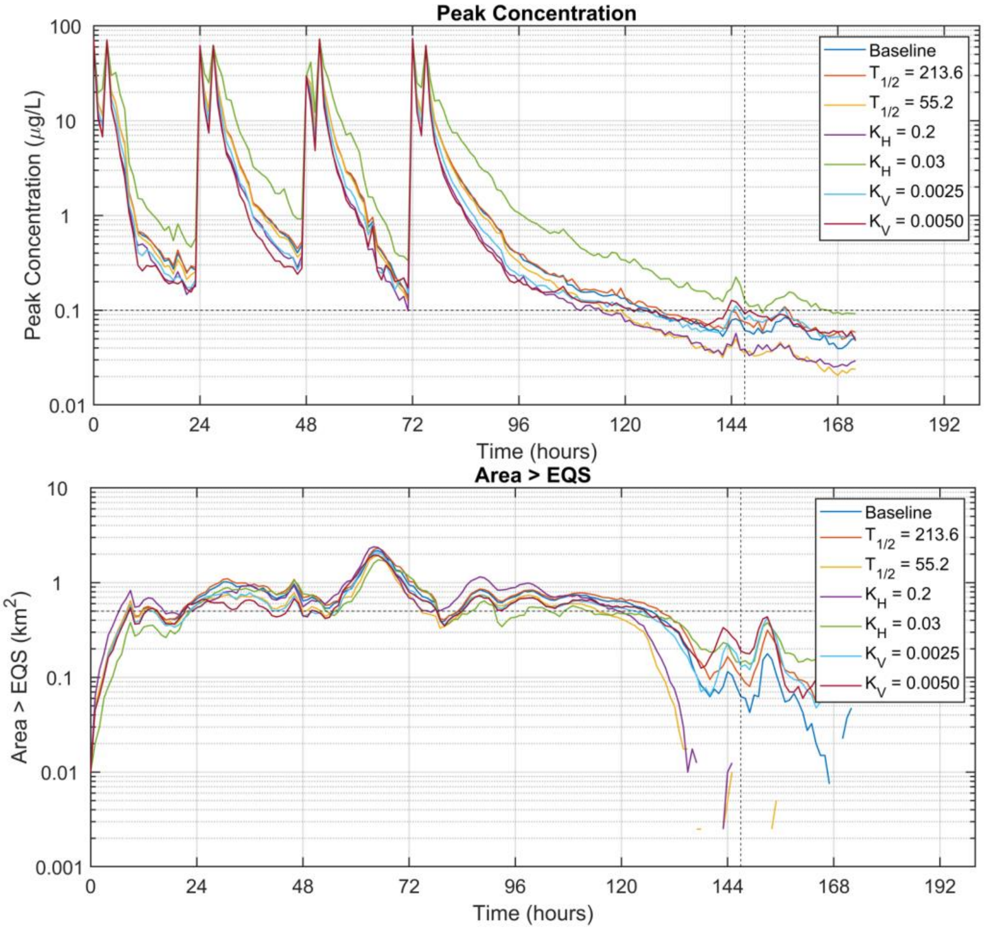

Figure 16. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, nineth and tenth set of model runs (Table 4). The model was run at neap tides from October 2018 with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient 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 = 147 h) of 0.1 g/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.7 3-Hour EQS

The 3-hour mixing zone is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 11.9 cm s^{-1} was used from ID113 (Table 1) which was thought to be a representative value for the surface 0-5m layer at Rum. The parameter values used in the calculation of the 3-hour mixing zone ellipse area are shown in Table 6.

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 8th September 2016) are shown in Figure 17. For each treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.19 km^2) after 3 hours. The peak concentration of 120 µg L^{-1} decreased to less than 15 µg L^{-1} within the 3-hour period.

For spring tide releases (first release on 15th September 2016), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 18). As for the neap tide simulation, the peak concentrations fell by an order of magnitude within the three hours.

This demonstrates that the discharge quantity of 1.23 kg of azamethiphos from each of the eight proposed 160m pens at Rum should not breach the 3-hour Environmental Quality Standard.

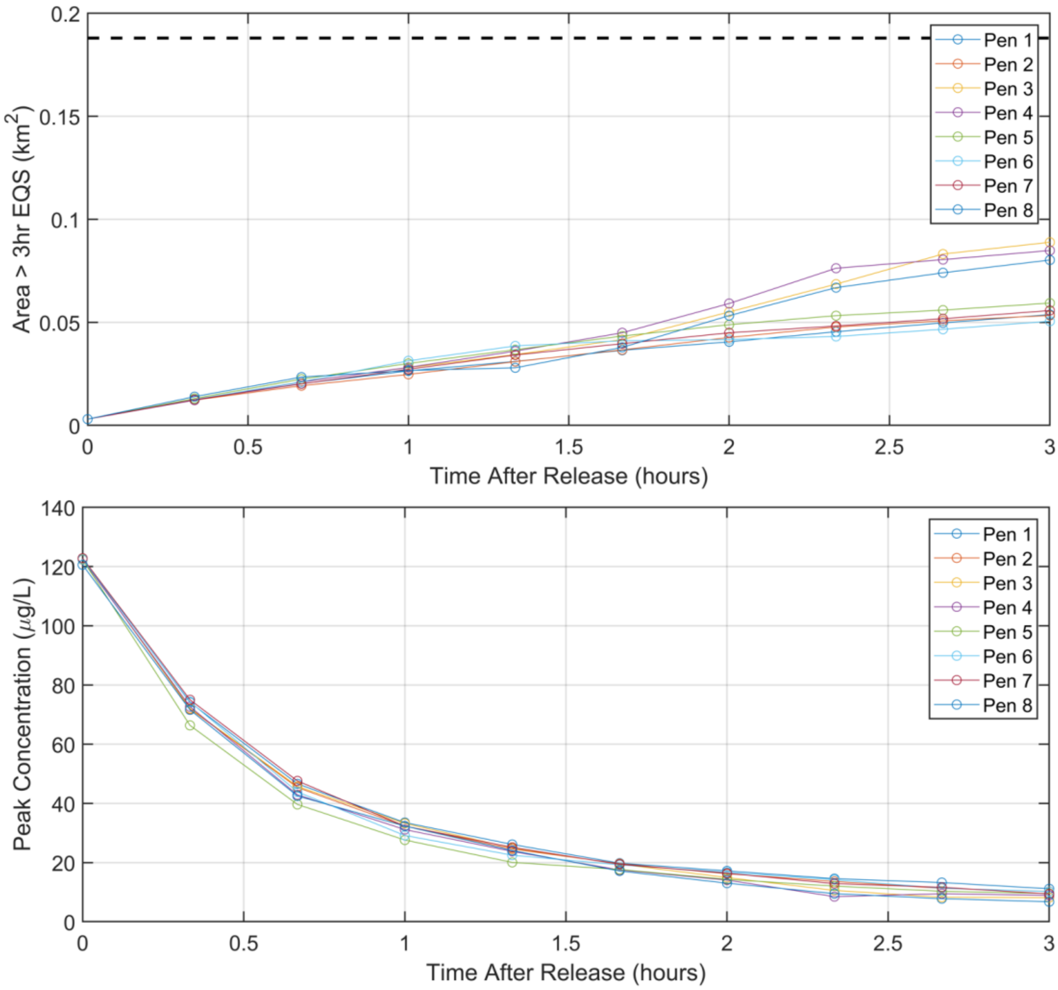

Figure 17. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

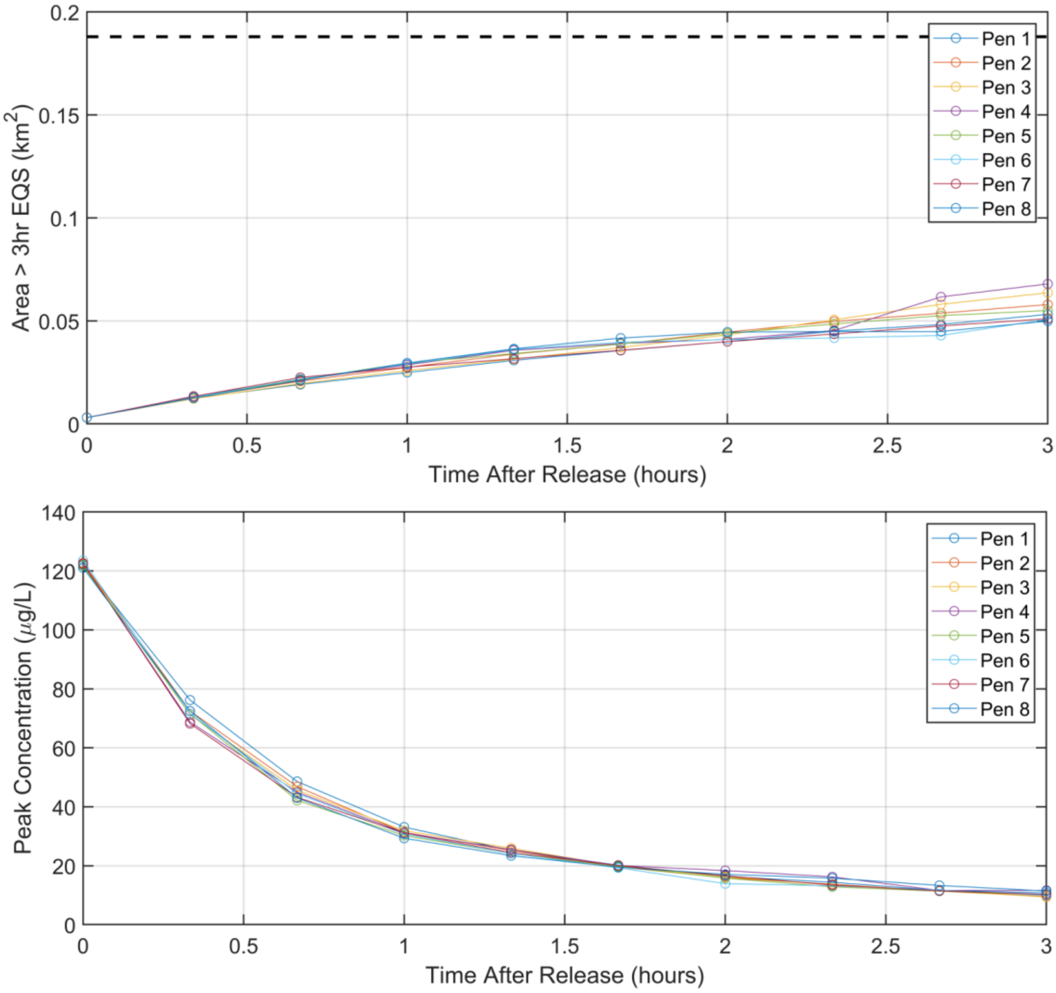

Figure 18. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area indicated (---).

3.8 Cumulative Modelling

Figure 19 shows the cumulative dispersion simulation at neap tide. After 24 hours, as the second days treatment was discharged at Muck, patches of medicine are evident. The maximum concentration at this time was ~100 µg/L, due to the release of the second treatment. After 4 days, the first 5 treatments have already been released from Muck and the first two treatments released from Rum. At this time, patches of medicine are evident from the previous days releases but they have rapidly dispersed and are already down to concentration levels of the same degree as the MAC (0.04 µg/L). After 7 days, the treatments have completed at both Muck and Rum, patches of medicine are now evident in the Cuillin Sound and the peak concentration is still at ~120 µg due to the final release from each site. At the EQS time of 10 days (72 hours after the final treatments), patches of medicine are still evident, however concentrations have decreased rapidly. It is clear from the dispersion simulation that the medicine released from Rum does not interact with any of the discharged medicine patches from Muck.

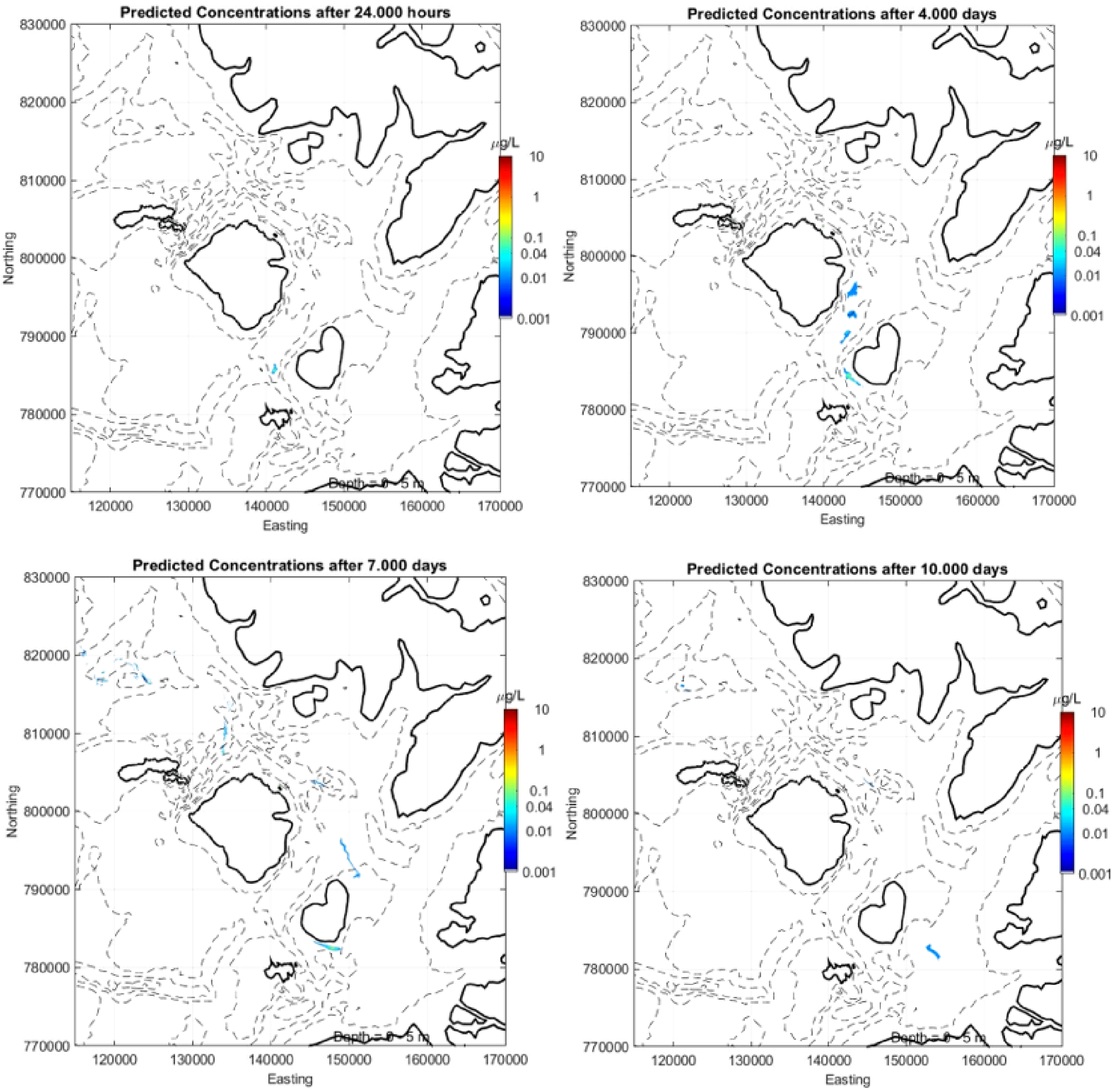

Figure 19. Dispersion simulation over neap tide at Rum and its neighbouring site Muck, following the treatment schedule described in Table 9. Start day = 20. The pens for each site are marked (•).

Figure 20 shows the mean concentration over the last 96 hours of the cumulative modelling simulations performed over both neap and spring tides. Time series of peak concentration and area exceeding the EQS for both sites over neap and spring tides are shown in Figure 21 and Figure 22 respectively. Site-specific modelling has been undertaken at Muck (Mowi Scotland, March 2022) to inspect the medicine dispersion in more detail.

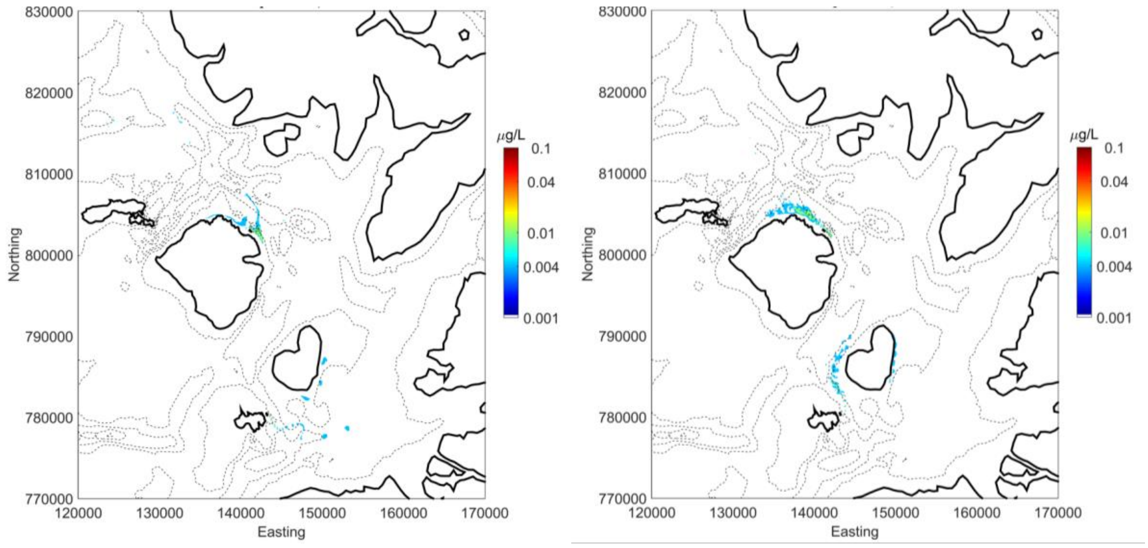

Figure 20. Mean predicted concentrations over the last 96 hours of the treatment scenario described in Table 9, over neap tide (left) and spring tide (right).

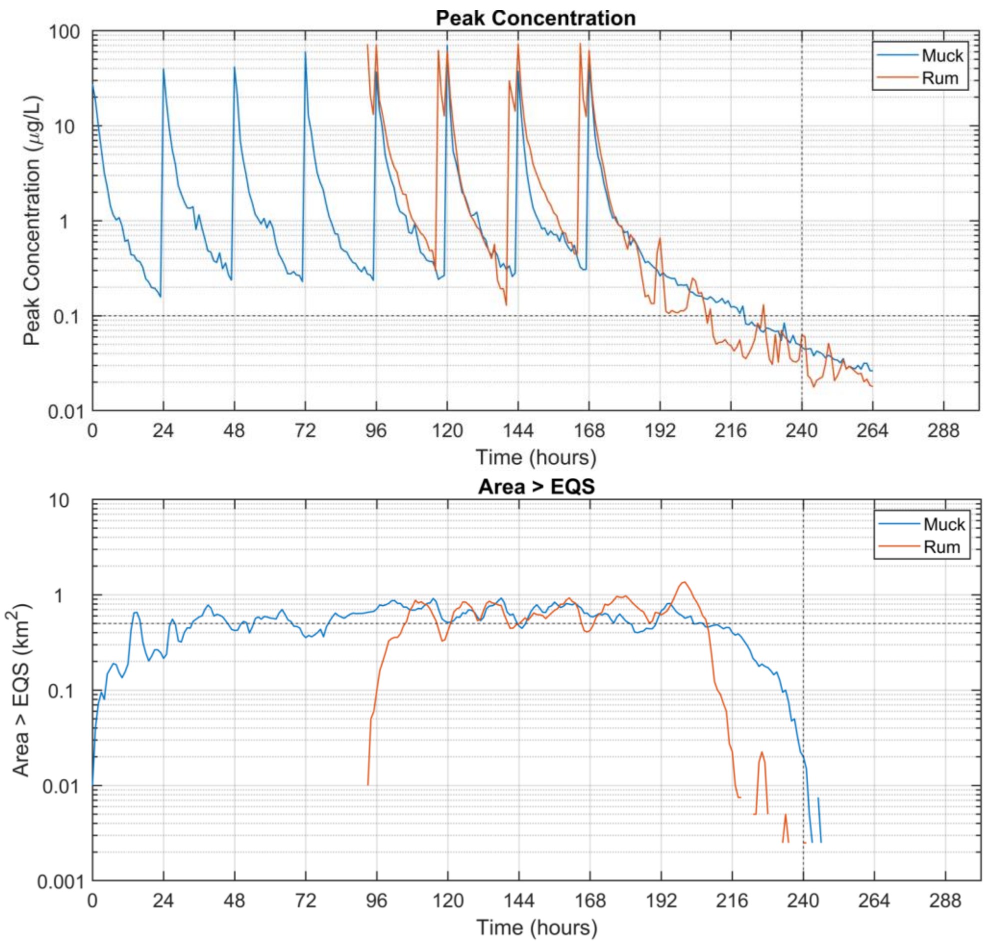

Figure 21. Time series of maximum concentration (top) and area exceeding the EQS (bottom) for the cumulative modelling of both sites over neap tide (STARTDAY = 20). The MAC and area limits 72 hours after the final treatment (Time = 240 hours) of 0.1 µg/L and 0.5 km² respectively are indicated by the horizontal dashed lines.

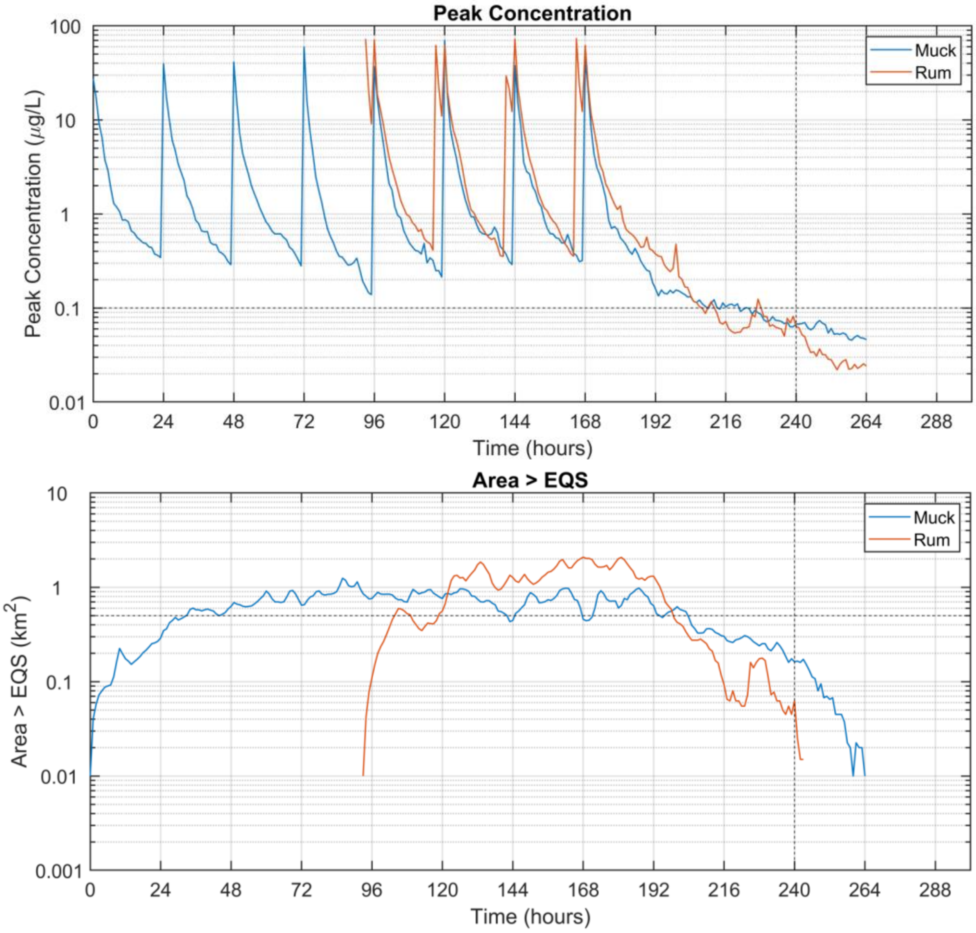

Figure 22. Time series of maximum concentration (top) and area exceeding the EQS (bottom) for the cumulative modelling of both sites over spring tide (STARTDAY = 27). The MAC and area limits 72 hours after the final treatment (Time = 240 hours) of 0.1 µg/L and 0.5 km² respectively are indicated by the horizontal dashed lines.

3.9 Interaction with Sensitive Features

Due to the dispersive nature of the Small Isles area, discharges of medicine from both Rum and Muck were included to look at the risk of medicine influence to the near-by PMF (Figure 7). Figure 23 shows the mean and maximum concentrations within the PMF area every hour for the top 5m of the water column over neap tide. The maximum concentration within the PMF area breached the 72hr MAC on two separate occasions, once between 149 and 154 hours and the second between 169 and 187 hours, both for relatively short periods of time (5 hours and 18 hours respectively). Figure 24 shows the proportion of the PMF area that had concentrations above the 3hr and 72hr MACs at any time within the 265-hour simulation over neap tide. This showed that at the peak, less than 9% of the PMF area breached the 72hr MAC and less than 4% of the area breached the 3hr MAC at any time.

Since the PMF is a benthic feature (burrowed mud), Figure 25 shows the concentration levels within the PMF area in a 5m layer above the seabed. It shows that for the duration of the simulation (265 hours), the concentration of Azamethiphos was at zero throughout.

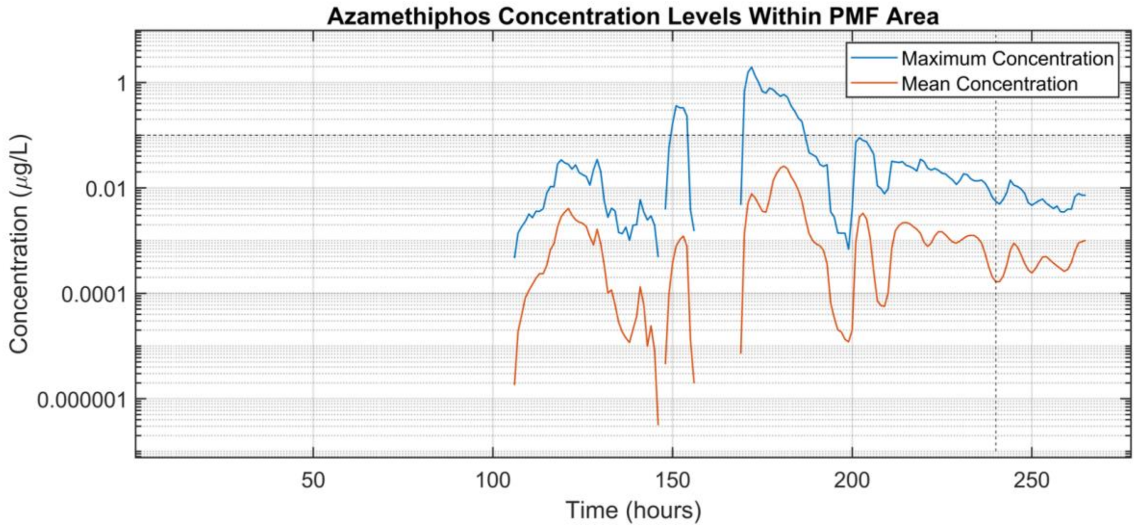

Figure 23. Maximum and mean Azamethiphos concentration levels within PMF area over Neap tide (depth = 0 - 5m). The 72 hr MAC value is denoted by the horizontal dashed line, 72 hr after final treatment denoted by vertical dashed line (Time = 240 hours)

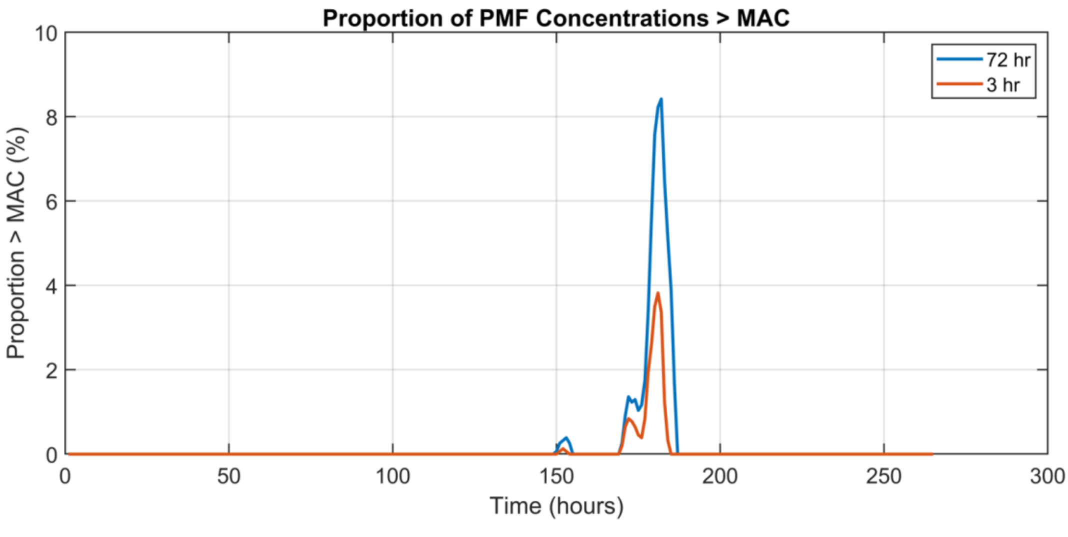

Figure 24. Proportion of PMF area over Neap tide (depth = 0 - 5m) with Azamethiphos concentrations greater than the 72 hour and 3 hour MAC

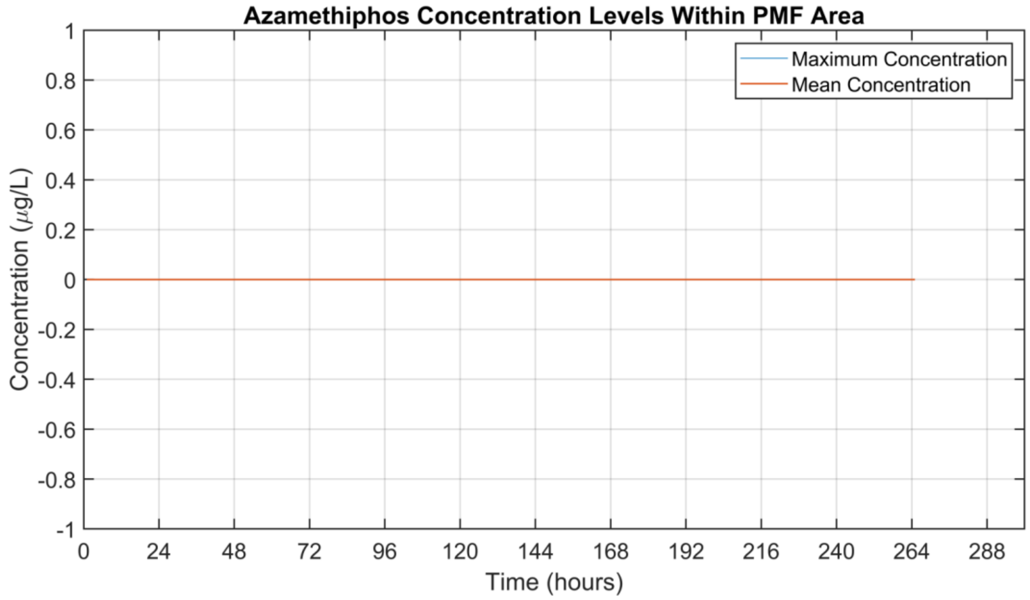

Figure 25. Maximum and mean Azamethiphos concentration levels within PMF area over Neap tide in the 5 m thick layer above the seabed.

The modelling was repeated for spring tides. Figure 26 shows the mean and maximum concentrations within the PMF area every hour for the top 5m of the water column over spring tide. The maximum concentration within the PMF area breached the 72hr MAC on a few separate occasions, but only for very short periods of time. Figure 27 shows the proportion of the PMF that had concentrations above the 3hr and 72hr MACs at any time within the 265-hour simulation over spring tide. This showed that at the peak, less than 10% of the area breached the 72 hr MAC and less than 3% of the area breached the 3hr MAC at any time. Figure 28 shows the concentration levels within the PMF area in a 5m layer above the seabed over spring tide. It again shows that for the duration of the simulation (265 hours), the concentration of Azamethiphos was at zero throughout. These results demonstrate that the medicine influence on this special feature is low.

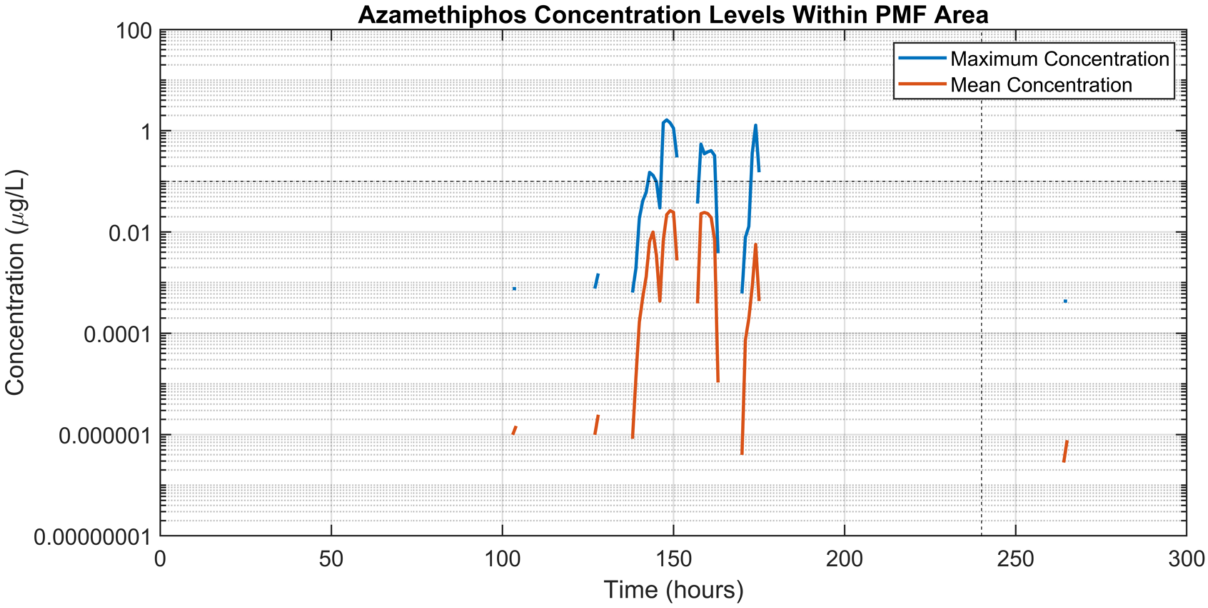

Figure 26. Maximum and mean Azamethiphos concentration levels within PMF area over Spring tide (depth = 0 - 5m). The 72 hr MAC value is denoted by the horizontal dashed line, 72 hr after final treatment denoted by vertical dashed line (Time = 240 hours)

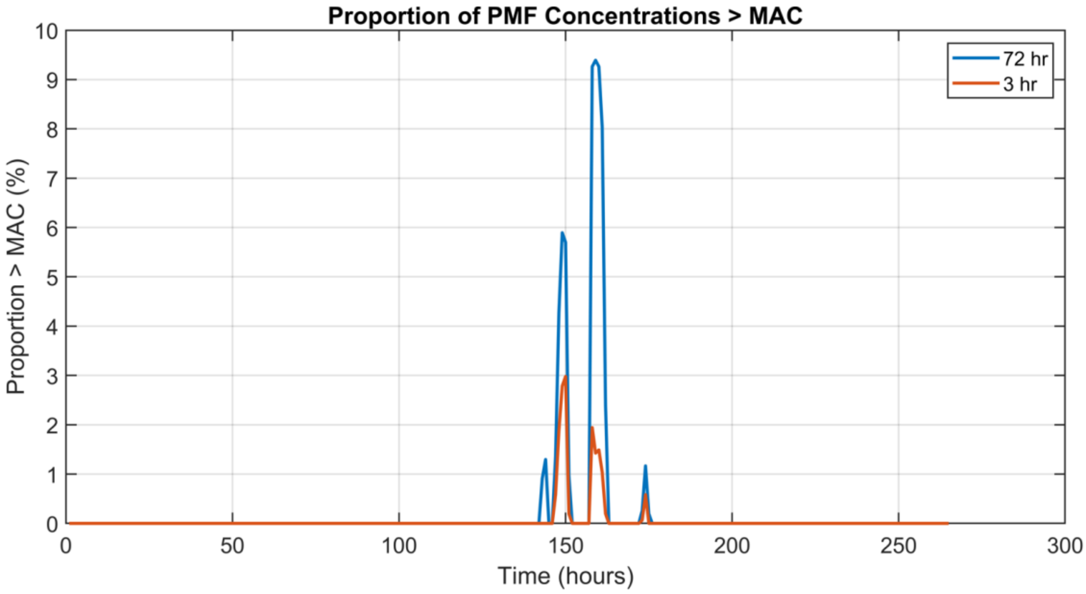

Figure 27. Proportion of PMF area over Spring tide (depth = 0 - 5m) with Azamethiphos concentrations greater than the 72 hour and 3 hour MAC

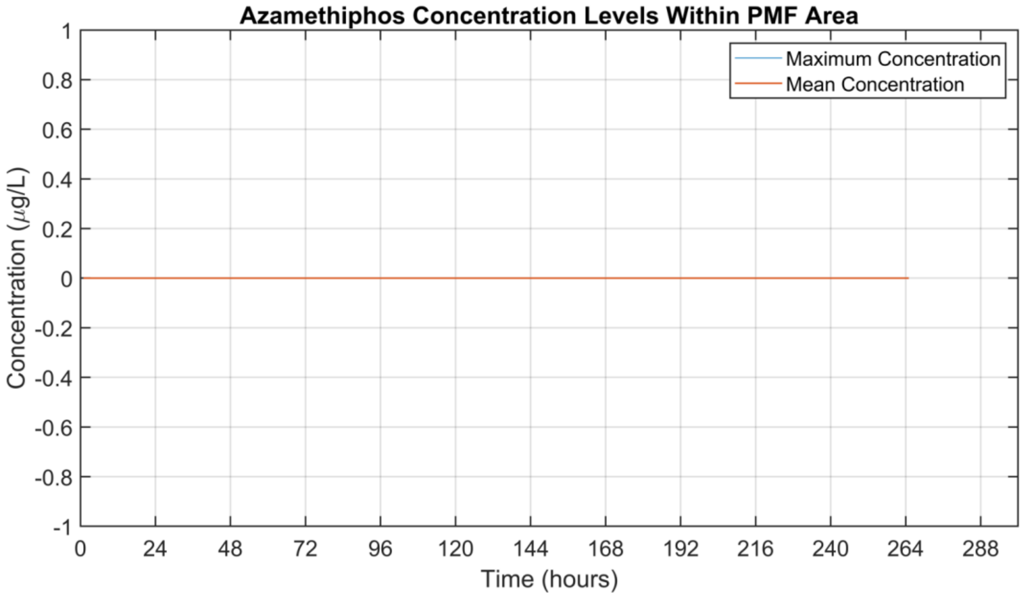

Figure 28. Maximum and mean Azamethiphos concentration levels within PMF area over Spring tide in the 5 m thick layer above the seabed.

4 SUMMARY AND CONCLUSIONS

A total of 31 dispersion simulations have been performed to assess whether bath treatments at Rum salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 2 pen treatments a day was simulated. Each pen required 1.23 kg of azamethiphos for treatment, resulting in a total discharge over 4 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 10.

Table 10. Summary of Results

Site Details	
Site Name:	Rum
Site Location:	Isle of Rum
Peak Biomass (T):	3,300
Pen Details	
Number of Pens:	8
Pen Dimensions:	160m circumference
Working Depth (m):	15
Pen Group Configuration:	2 x 4
Azamethiphos	
Recommended 3hr Consent (kg):	1.23
Recommended 24hr Consent (kg):	2.46

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 2.46 kg, should consistently comply with the EQS. The peak concentration during the baseline simulation after 147 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 except one, including sensitivity testing, the EQS and MAC criteria were met. Further simulations over a neap tide from 2018 demonstrated that the modelled treatment regime consistently complied with the relevant EQS and MAC. For the simulation during spring tides, greater dispersion meant that the MAC and EQS were met very comfortably. Therefore, it is believed that the requested daily quantity of 2.46 kg of azamethiphos can be safely discharged at Rum without breaching the MAC or EQS.

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

The simulations of potential interaction with the nearby PMF indicated that a small proportion of the surface water in the PMF area may briefly experience medicine concentrations above the 3-hour and 72-hour EQS. However, the PMF is a benthic feature (burrowed mud), and near-bed medicine concentrations were consistently zero through the simulations for both spring and neap tides.

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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