Bath Medicine Dispersion Modelling Report Caolas a Deas East, Loch Shell

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at **Caolas a Deas East** salmon farm in Loch Shell will comply with pertinent environmental quality standards. Realistic treatment regimes, with 1 pen treatment per day for four days, were simulated. Each pen required 0.917 kg of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) for treatment, resulting in a daily release of 0.917 kg and a total discharge over four days of 3.667 kg. Simulations were performed separately for neap and spring tides, and the sensitivity of the results to key model parameters was tested.

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 0.917 kg, should comfortably comply with the EQS. The peak concentration during the baseline simulation after 144 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. Results are summarised in Table 1.

Table 1. Summary of Results

SITE DETAILS			
Site Name:		Caolas a Deas East	
Site location:		Loch Shell	
Peak biomass (T):		1701	
PEN DETAILS			
Number of pens:		4	
Pen dimensions:		160m Circumference	
Working Depth (m):		20	
Pen group configuration:		1 x 4, 100m matrix	
HYDROGRAPHIC SUMMARY		**ID367**	**ID424**
Near-Surface Currents	Mean Speed (m/s)	0.052	0.059
	Residual Speed (m/s)	0.020	0.018
	Residual Direction (°G)	164	124
	Tidal Amplitude Parallel (m/s)	0.069	0.089
	Tidal Amplitude Normal (m/s)	0.039	0.039
	Major Axis (°G)	145	125
BATH TREATMENTS			
Recommended consent mass – 3-hr Azamethiphos (kg)		0.917	
Recommended consent mass – 24-hr Azamethiphos (kg)		0.917	
Recommended consent mass – 6-hr Deltamethrin (kg)		0.020	

The requested 24-hour mass is substantially larger than the amount predicted by the standard bath model, BathAuto, but the latter is known to be highly conservative, because it does not account for horizontal shearing and dispersion of medicine patches due to spatially-varying current fields, processes which are known to significantly influence dispersion over times scales greater than a few hours (e.g. Okubo, 1971; Edwards, 2015), as illustrated in Figure 9.

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 at the **Caolas a Deas East** marine salmon farm in **Loch Shell** (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 December 2023 (SEPA, 2023b). Dispersion modelling results for the neighbouring site at Caolas a Deas West are described in a separate report (Mowi, 2024b).

*Figure 1. Location of Loch Shell (top) in the Western Isles and the location of the 160m pens at the Caolas a Deas West and East sites (**O**, bottom). The boundary of the planning area is indicated (**—**).*

1.1 Site Details

The site is situated in the outer part of Loch Shell (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:		Caolas a Deas East
Site location:		Loch Shell
Peak biomass (T):		1701
Proposed feed load (T/yr):		4345
Proposed treatment use:		Azamethiphos
PEN DETAILS		
Group location:		NB 364 098
Number of pens:		4
Pen dimensions:		160m circumference
Grid matrix (m)		100
Working Depth (m):		20
Pen group configuration:		1 x 4
Pen group orientation (°G):		130
Pen group distance to shore (km):		250
Water depth at site (m):		~40
HYDROGRAPHIC DATA		
	ID367	**ID424**
Current meter position:	136687E 909860N	136515E 909986N
Depth at deployment position (m, wrt CD):	45.5	52.0
Surface bin centre height above bed (m):	39.7	-2.5 below surface
Middle bin centre height above bed (m):	31.7	-6.0 below surface
Bottom bin centre height above bed (m):	3.7	-10.0 below surface
Duration of record (days):	85	53
Start of record:	16:00 09-Feb-2021	11:02 06-Oct-2023
End of record:	07:40 06-May-2021	07:57 29-Nov-2023
Current meter averaging interval (min):	20	20
Magnetic correction to grid North:	-3.78	-3.78

2 METHODS

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 (marine) 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 marine modelling approach is described in full in Mowi (2024a) and is only summarised here.

For the hydrodynamics, the FVCOM model was used. FVCOM (Finite Volume Community Ocean Model) is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model developed by the University of Massachusetts School of Marine Science and the Woods Hole Oceanographic Institute (Chen et al., 2003). The model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure submodels. The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is presented using generalized terrain-following coordinates. The General Ocean Turbulent Model (GOTM) developed by Burchard's research group in Germany (Burchard, 2002) has been added to FVCOM to provide optional vertical turbulent closure schemes. FVCOM is solved numerically by a second-order accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. This approach combines the best features of finite-element methods (grid flexibility) and finite-difference methods (numerical efficiency and code simplicity) and provides a much better numerical representation of both local and global momentum, mass, salt, heat, and tracer conservation. The ability of FVCOM to accurately solve scalar conservation equations in addition to the topological flexibility provided by unstructured meshes and the simplicity of the coding structure has make FVCOM ideally suited for many coastal and interdisciplinary scientific applications.

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. Further details of the FVCOM model and simulations are given in Mowi (2024a).

For the particle tracking component, Mowi's in-house model unptrack (Gillibrand, 2022) was used. The model used the hydrodynamic flow fields from the FVCOM 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, the mass of 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, and horizontal and vertical diffusion. The choice of horizontal diffusion coefficient was informed by dye release experiments in Loch Shell. After 72 hours, concentrations of medicine were calculated and compared with the relevant Environmental Quality Standard (EQS). Here, we have modelled the dispersion of azamethiphos following a treatment scenario 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 covered Loch Shell and adjacent coastal waters (Figure 2). Model resolution was enhanced in the Loch Shell region particularly around the Mowi sites at Caolas a Deas East and West (Figure 3).

The spatial resolution of the model varied from about 25 m in some inshore waters to about 450 m along the open boundary. The mesh was refined down to about 45 – 50 m in the area of the 160 m circumference (51 m diameter) pens (Figure 3) and is completely adequate for modelling dispersion of solutes. In total, the model consisted of 37,604 nodes and 71,795 triangular elements.

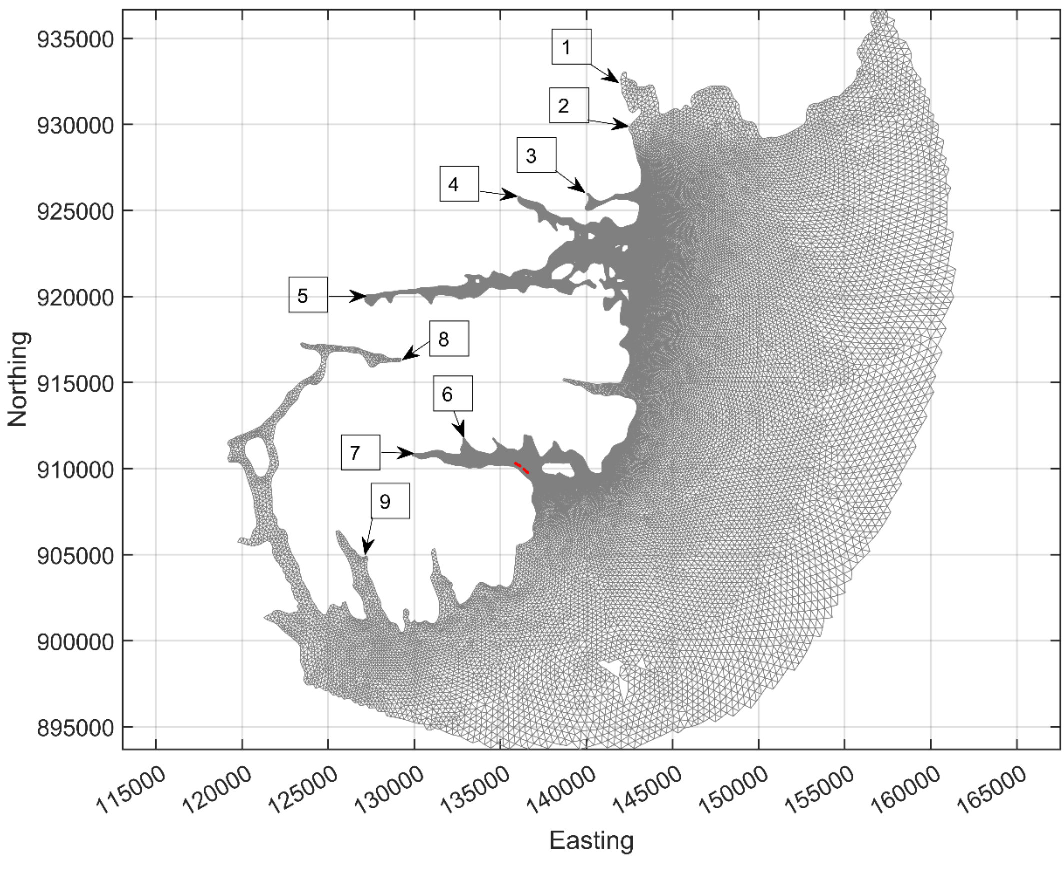

Figure 2. The model mesh and domain for the Outer Loch Shell modelling study. The proposed cage locations (●) are indicated, as are locations of freshwater discharge (→).

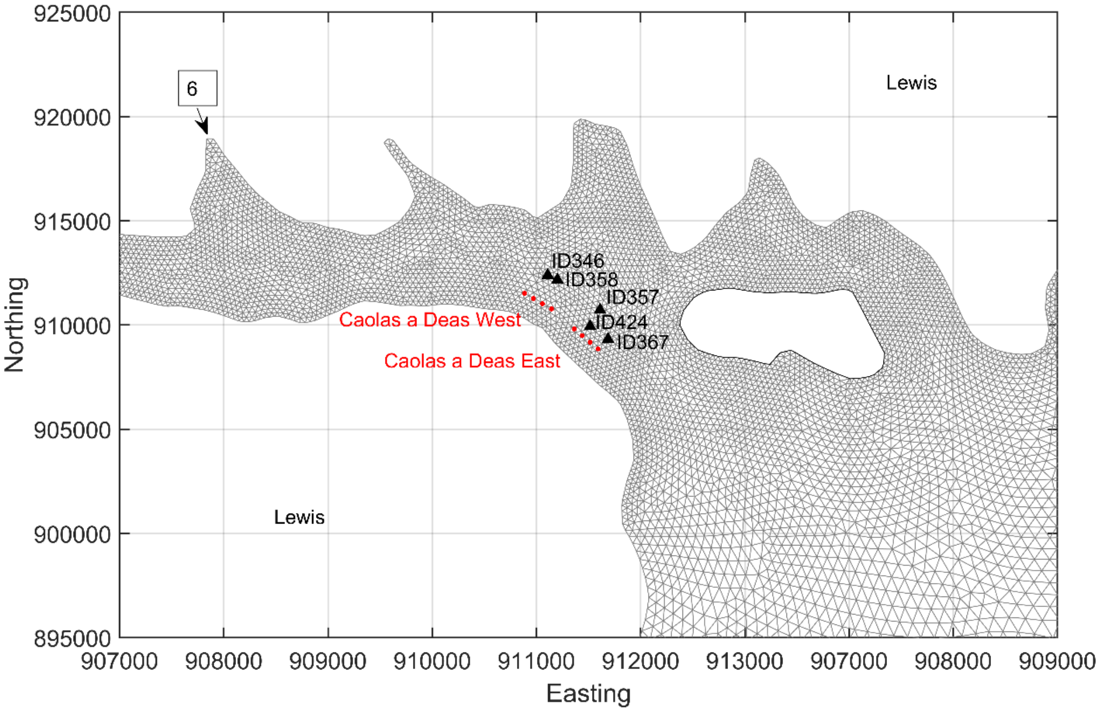

Figure 3. ADCP deployment locations ID346, ID357, ID358, ID367 and ID424 (▲) and locations of freshwater discharge (→) are also indicated.

Model bathymetry was taken from the UK Hydrographic Office (UKHO 2024) data portal, supplemented by a multibeam survey undertaken in June 2021 (Figure 4). The combined data were interpolated onto the Shell model mesh.

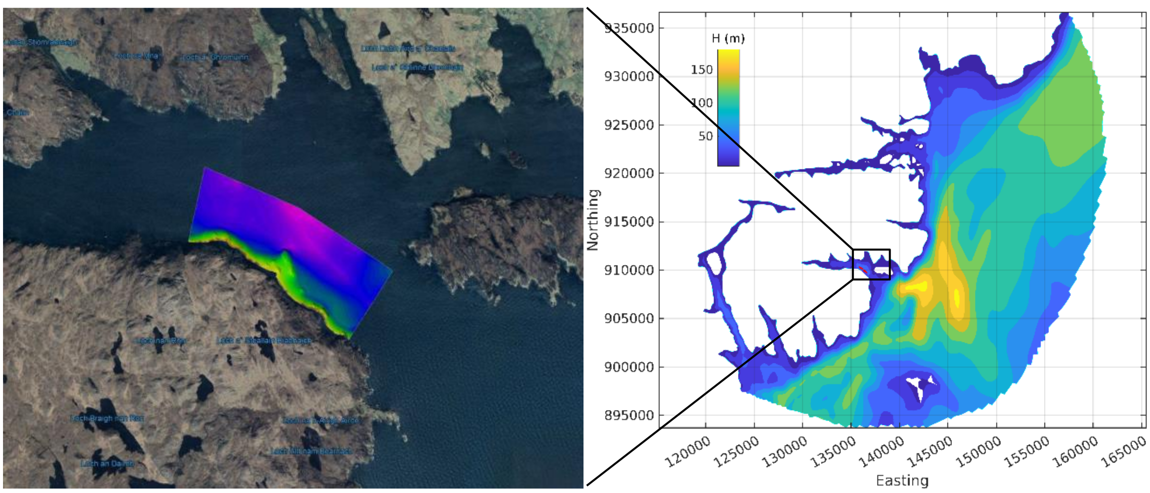

Figure 4. Multibeam survey of bathymetry around Caolas a Deas farm sites from December 2020 (left). Model water depths (H, m) in the model domain (right), incorporating the multibeam data. The proposed cage locations are indicated (●).

The model was forced along its open boundary by time series of sea surface height (SSH) at each boundary node for the relevant simulation periods; FVCOM appears to perform better with time series boundary forcing than when tidal constituents are used. The SSH time series were generated using the RiCOM hydrodynamic model (Walters and Casulli, 1998; Gillibrand et al., 2016b) on the ECLH grid (Price et al., 2016), which was, in turn, forced by eight tidal constituents (O_1, K_1, Q_1, P_1, M_2, S_2, N_2, K_2) taken from the full Scottish Shelf model (SSM). Spatially- and temporally-varying wind speed and direction data were taken from the Weather Research and Forecast (WRF) model results, deployed operationally as part of the WestCOMS modelling system (Aleynik et al., 2016).

Stratification was expected to be moderate in this location and the model was run in 3D baroclinic mode. Ten layers in the vertical (eleven sigma levels) were used in the simulations, with layers concentrated near the surface and seabed (Mowi, 2024a). Climatological river flow data were used, taken from the Marine Scotland Scottish Shelf Model climatology (De Dominicis et al., 2018). Nine freshwater discharges into the model domain were specified (Figure 2), with two going directly into Loch Shell.

2.2 Hydrodynamic Model Calibration

The hydrodynamic model was calibrated against current data and seabed pressure data, measured at the Shell site using Acoustic Doppler Current Profilers (ADCP). Data were available at five locations (Figure 3) between 2020 and 2023. The five ADCP deployments extended over 330 days in total. Calibration was performed by adjusting the bed roughness and horizontal viscosity/diffusivity coefficients to obtain the best fit against the sea surface height and current velocity data. The model ran for the same period as the observations and the modelled surface elevation and velocity at the three data locations were evaluated against the observed data. Details of the calibrations are given in Mowi (2024a).

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 for input, although current velocities are interpolated temporally and spatially to individual particle locations within UnPTRACK.

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 treatment scenario assumed 1 pen can be treated per day. This is the quickest practicable schedule for installation of tarpaulins, dosage, and removal of tarpaulins for 160 m pens.

To simulate the worst-case scenario, the dispersion modelling was initially conducted using flow fields over a period of seven 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 the quantity of medicine able to be discharged and meet the required EQS is least. Later simulations tested dispersion during spring tides.

A treatment depth of 4.5 m was chosen as a realistic net depth during application of the medicine for 160 m 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 3.667 kg of azamethiphos released during treatment of the whole farm (four pens). Particles were released from random positions within a pen radius of the centre and within the 0 – 4.5 m depth range. Each numerical particle represented 10 mg of azamethiphos.

Each simulation ran for a total of 169 hours. This covered the treatment period (72 hours), a dispersion period to the EQS assessment after 144 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. Medicine concentrations were calculated from these archived results. Concentrations were calculated on a grid of 25 m x 25 m squares over the surface 5 m layer. Using a regular grid for counting makes calculating particle concentrations and presenting the results easier, and provides a known resolution of the calculated concentrations. 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^{-1}) 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) Horizontal diffusion coefficient, K_H
(ii) Vertical diffusion coefficient, K_V
(iii) Time of release

The dispersion simulations were performed separately over neap and spring tides during 2021 (Figure 5). Further sets of simulations were performed at neap tides in 2023 to confirm the adequacy of dispersion during the weakest tides (Figure 6).

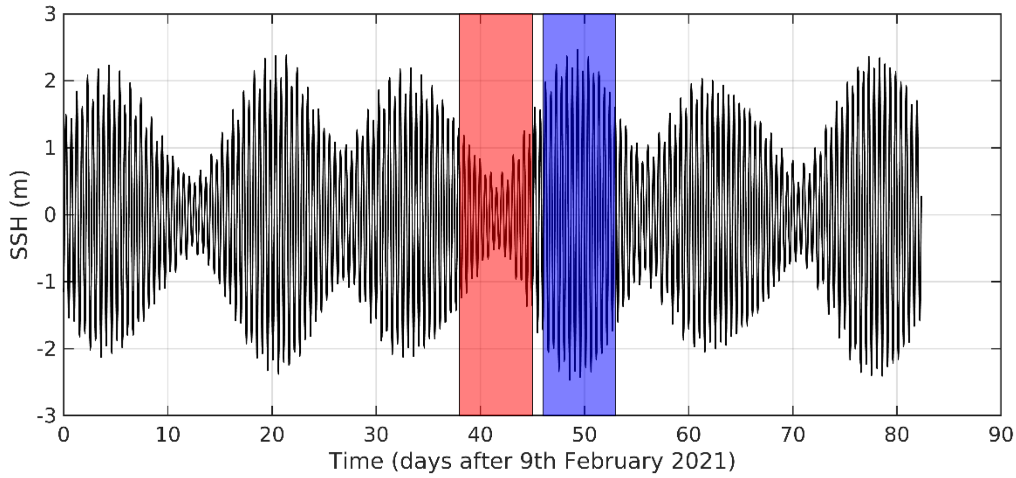

Figure 5. Measured sea surface height (SSH) in Loch Shell from 9th February – 7th May 2021 (ID367). Dispersion simulations were performed over the period of neap tides highlighted in red.

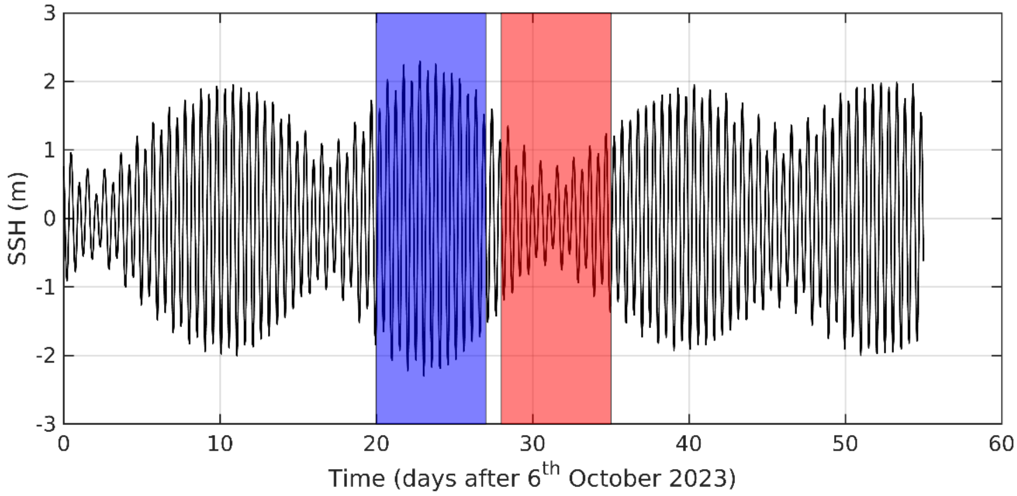

Figure 6. Sea surface height (SSH) in Loch Shell from 6th October – 30th November 2023 (ID424). Dispersion simulations were performed over periods of neap tides (highlighted in red) and spring tides (blue).

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.

The simulations performed are listed in Table 4. In Runs 6 – 11 and 17 – 22, the release schedule was set forward/back 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 at Caolas a Deas East simulated by the dispersion model. The release time is relative to the start of the neap or spring periods highlighted in Figure 5 and Figure 6.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (kg)	Release Time (hr)
1	136362	909962	4.5	0.917	0
2	136438	909898	4.5	0.917	24
3	136514	909834	4.5	0.917	48
4	136591	909770	4.5	0.917	72

Table 4. Dispersion model simulation details for the treatment simulations of four pens at Caolas a Deas East.

Set	Run No.	$T_{1/2}$ (h)	K_H	K_V	Start Time
Neap Tides, Start day = 39 (19 March 2021, ID367)					
Baseline	1	134.4	0.1	0.001	00:00
1	2	134.4	0.05	0.001	00:00
	3	134.4	0.15	0.001	00:00
	4	134.4	0.1	0.0025	00:00
	5	134.4	0.1	0.0050	00:00
2	6	134.4	0.1	0.001	00:00 -6h
	7	134.4	0.1	0.001	00:00 -4h
	8	134.4	0.1	0.001	00:00 -2h
	9	134.4	0.1	0.001	00:00 +2h
	10	134.4	0.1	0.001	00:00 +4h
	11	134.4	0.1	0.001	00:00 +6h
Spring Tides, Start day = 47 (27 March 2021, ID367)					
3	12	134.4	0.1	0.001	00:00
4	13	134.4	0.05	0.001	00:00
	14	134.4	0.15	0.001	00:00
	15	134.4	0.1	0.0025	00:00
	16	134.4	0.1	0.0050	00:00
5	17	134.4	0.1	0.001	00:00 -6h
	18	134.4	0.1	0.001	00:00 -4h
	19	134.4	0.1	0.001	00:00 -2h
	20	134.4	0.1	0.001	00:00 +2h
	21	134.4	0.1	0.001	00:00 +4h
	22	134.4	0.1	0.001	00:00 +6h
Neap Tides, Start day = 29 (03 November 2023, ID424)					
6	23	134.4	0.1	0.001	00:00
	24	134.4	0.05	0.001	00:00
	25	134.4	0.15	0.001	00:00
	26	134.4	0.1	0.0025	00:00
	27	134.4	0.1	0.0050	00:00
Spring Tides, Start day = 21 (26 October 2023, ID424)					
7	28	134.4	0.1	0.001	00:00
	29	134.4	0.05	0.001	00:00
	30	134.4	0.15	0.001	00:00
	31	134.4	0.1	0.0025	00:00
	32	134.4	0.1	0.0050	00:00

2.5 Cumulative Treatment

Although not required (SEPA, 2023a), simulations were performed of the cumulative dispersion following sequential treatments at both Caolas a Deas West and Caolas a Deas East sites. One pen was treated per day, with all eight pens across the combined sites treated sequentially at 24-hour intervals (Table 5). The simulation was performed for the same neap and spring tides from 2021 shown in Figure 5, but started two days earlier to account for the extra treatments (and also finished two days later). Model parameters for these simulations were the baseline standard values (Table 6).

Table 5. Details of the combined treatment at Caolas a Deas West (Pens 1 – 4) and Caolas a Deas East (Pens 5 – 8) simulated by the model. The release time is relative to the start of the simulation.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (kg)	Release Time (hr)
1	135885	910304	4.5	0.917	0
2	135971	910254	4.5	0.917	24
3	136057	910204	4.5	0.917	48
4	136144	910154	4.5	0.917	72
5	136362	909962	4.5	0.917	96
6	136438	909898	4.5	0.917	120
7	136514	909834	4.5	0.917	144
8	136591	909770	4.5	0.917	168

Table 6. Dispersion model simulation details for the combined treatment simulations of eight pens at Caolas a Deas West and East.

Set	Run No.	$T_{1/2}$ (h)	K_H	K_V	Start Time
Neap Tides, Start day = 37 (17 March 2021, ID367)					
8	33	134.4	0.1	0.001	00:00
Spring Tides, Start day = 45 (25 March 2021, ID367)					
9	34	134.4	0.1	0.001	00:00

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, 2023b). 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 5.9 cm s^{-1} was used from the near-surface currents at 2.5 m below the moving sea surface from ID424 (Table 7), as most representative of the surface layer in which bath medicine dispersion occurs.

For the 3-hour EQS assessment, the baseline runs for neap and spring tides 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.

Table 7. Parameter values used in the calculation of the 3-hour and 6-hour mixing zone areas. The mean current speed is taken from ID424.

Parameter	Value
Mean current speed (ms^{-1})	0.059
Area of 160 m pen (km^2)	0.002037
Horizontal diffusion coefficient ($m^2\ s^{-1}$)	0.1
Distance from shore (km)	0.237
Mean water depth (m)	52.0
Treatment Depth (m)	5.0
3-hr Mixing zone area (km^2)	**0.093667**
6-hr Mixing zone area (km^2)	**0.264930**

2.7 Deltamethrin: 6-hour EQS

Deltamethrin simulations were performed to assess compliance with the 6-hour EQS (SEPA, 2023b). The 6-hour EQS is applied as a mixing zone EQS, whereby the area where concentrations exceed the EQS of 6 ng L^{-1} after 6 hours must be less than the 6-hour mixing zone. Like the 3-hour mixing zone, the 6-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. The calculated 6-hour mixing zone is shown in Table 7.

For the 6-hour EQS assessment, the baseline runs for neap and spring tides were repeated, but with a treatment mass of 0.020 kg of deltamethrin. The medicine half-life was set to zero. Results were output every 20 minutes and the runs were truncated, lasting only until 6 hours after the final treatment. The area of the medicine patch for each individual treatment was then calculated over the 6-hour period following its release, and the area exceeding 6 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 6-hour period.

2.8 Interactions with Special Features

No special features were by identified as being at risk from medicine treatments at Caolas a Deas East (SEPA, 2023a).

2.9 Diffusion Coefficients

Selection of the horizontal diffusion parameter, K_H, was informed by a dye release study conducted at the Caolas a Deas location on 23rd July 2020 by Anderson Marine Surveys Ltd (AMSL, 2020). Five separate releases of dye were made, and horizontal dispersion coefficients were estimated for each release using standard methods. A mean horizontal diffusivity for the location of **K_H = 0.15 m^2 s^{-1}** was derived (AMSL, 2020). This value will be used as part of the sensitivity testing of the model predictions.

Drogue releases were carried out simultaneously with the dye releases, using standard-pattern drogues with reduced sail depth (≈1 m, due to relatively shallow water depths), fitted with GlobalSat GPS dataloggers recording at 2-minute intervals. The data from both dye and drogue releases are provided to SEPA with this report.

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. Estimates of horizontal diffusivity can be made from these individual transects.

The analysis method is based on estimating the variance of the dye concentrations along the individual transects through the dye patch. The overall mean horizontal diffusivity from all the measurements made was 0.15 m^2 s^{-1}. There is considerable scatter in the data (Figure 7), arising from the difficulty of tracking dye in the marine environment which renders individual values highly uncertain; this difficulty is exacerbated in Scotland due to the limited quantities of dye that are permitted to be released, making it difficult to visually track the dye and take measurements that encompass the patch.

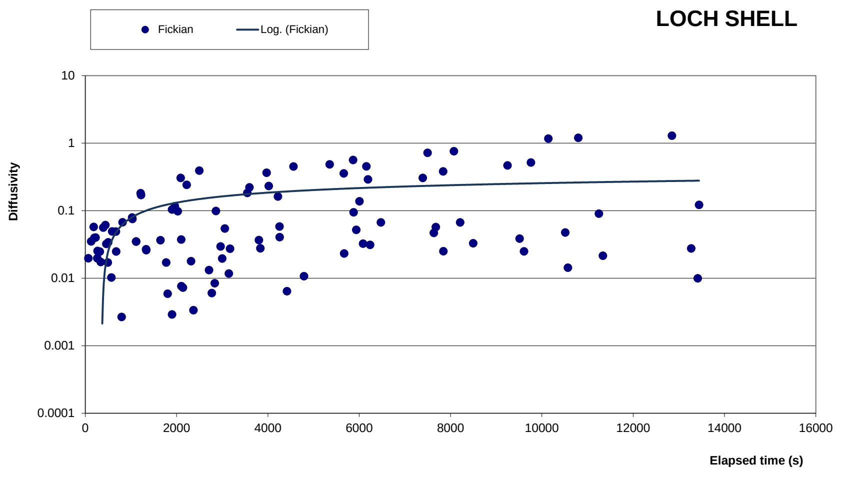

Figure 7. Estimated horizontal diffusivity (m^2 s^{-1}) from dye release experiments at Caolas a Deas, Loch Shell, on 23rd July 2020. The mean diffusivity was 0.15 m^2 s^{-1}.

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:

$$C_{max} = \frac{M}{4\pi H K_H t} \quad (1)$$

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_H is the horizontal diffusivity (m^2 s^{-1}), assumed equal in x- and ydirections, 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_H to be made.

For each dye release in Loch Shell, we 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 generally show that a value of K_H = 0.1 m^2 s^{-1} is a reasonable (and generally conservative) estimate of horizontal diffusivity, in that the measured peak concentrations decrease more quickly than the theoretical values for K_H = 0.1 m^2 s^{-1} (Figure 8). These data, and all other dye studies undertaken by Mowi in recent years, suggest that a horizontal diffusivity of 0.1 m^2 s^{-1} is a reasonable estimate of short term eddy diffusion in Scotland's coastal marine environment. A similar conclusion was reached by Dale et al. (2020) following dye releases conducted in Loch Linnhe and adjacent waters.

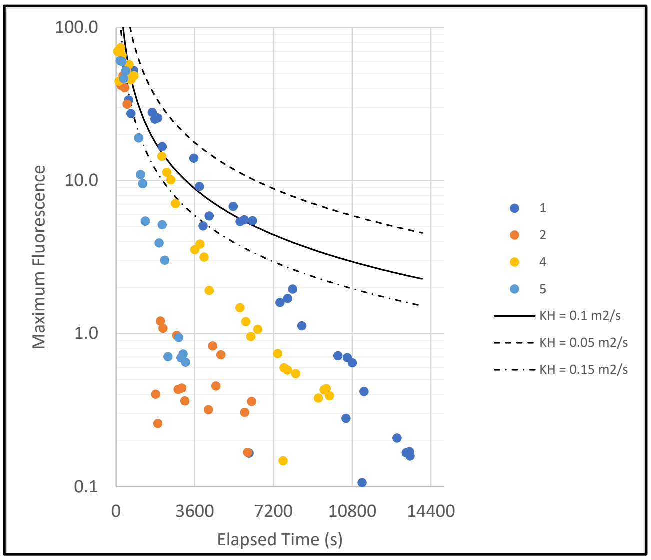

Figure 8. Maximum fluorescence (solid circles) measured following dye releases in Loch Shell in July 2020. Four sets of releases are shown; tracking of the third release was abandoned. The black lines indicate the rate at which the maximum concentration would fall at different horizontal diffusivities (K_H = 0.05 m^2 s^{-1}, 0.10 m^2 s^{-1} and 0.15 m^2 s^{-1}).

Most of the model simulations described in this report were conducted using a horizontal diffusion coefficient of K_H = 0.1 m^2 s^{-1} which provided some conservatism in the results; however, the sensitivity of the model to K_H was explored, using values of K_H = 0.05 m^2 s^{-1} and K_H = 0.15 m^2 s^{-1}.

3 RESULTS

3.1 Dispersion During Neap Tides, March 2021 (ID367)

A standard treatment of 4 x 160m pens, with a reduced net depth of 4.5 m and assuming a maximum of 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 0.917 kg, a daily (24-h) release of 0.917 kg and a total treatment release of 3.667 kg over 72 hours. The dispersion of the medicine during and following treatment from Run001 is illustrated in Figure 9. After 24 hours, as the second treatment was discharged, a small patch of medicine from the first treatment is evident to the south by the shore. The maximum concentration at this time was 100 µg L^{-1}, due to the release of the second treatment. After 36 hours, a larger patch of medicine is still evident to the southeast; the peak concentration at this time was about 0.35 µg L^{-1}. After 48 hours, as the third treatment was released, the earlier treatment patches have dispersed completely (Figure 9). The remaining concentration fields after 60, 72 and 144 hours show similar features: patches of medicine rapidly dispersing in the open waters to the east of Loch Shell.

The treatment schedule completed after 72 hours (3 days). At this time, the medicine released on earlier days was present in a patch near the entrance of Loch Shell with concentrations slightly higher than the EQS (0.04 µg L^{-1}). 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. After 4 days, 24 hours after the final treatment, the final patches of medicine were dispersing rapidly and by 144 hours (72 hours after final treatment) the medicine had completely dispersed.

The time series of maximum concentration from the simulation is shown in Figure 10. The four peaks in concentration of ~100 µg L^{-1} following each treatment event over the first three days are evident. Following the final treatment after 72 hours, the maximum concentration fell steadily away (Figure 10). With a default half-life of 134.4 h (5.6 days), the maximum concentration seventy-two hours after the final treatment (time = 144 hours) was around 0.01 – 0.02 µg L^{-1}, well below the maximum allowable concentration (MAC) of 0.1 µg L^{-1}.

The area where the EQS of 0.04 µg L^{-1} was exceeded peaked at about 1.2 km^2 during treatment on Days 3 and 4, but had fallen below 0.5 km^2 within 24 h of the final treatment; by 72 h after the final treatment, the exceeded area was zero (Figure 10).

These results indicate that environmental quality standards were comfortably achieved with this treatment scenario. In the following sections, the sensitivity of the model results to the diffusion coefficients and tidal state at the time of release are examined.

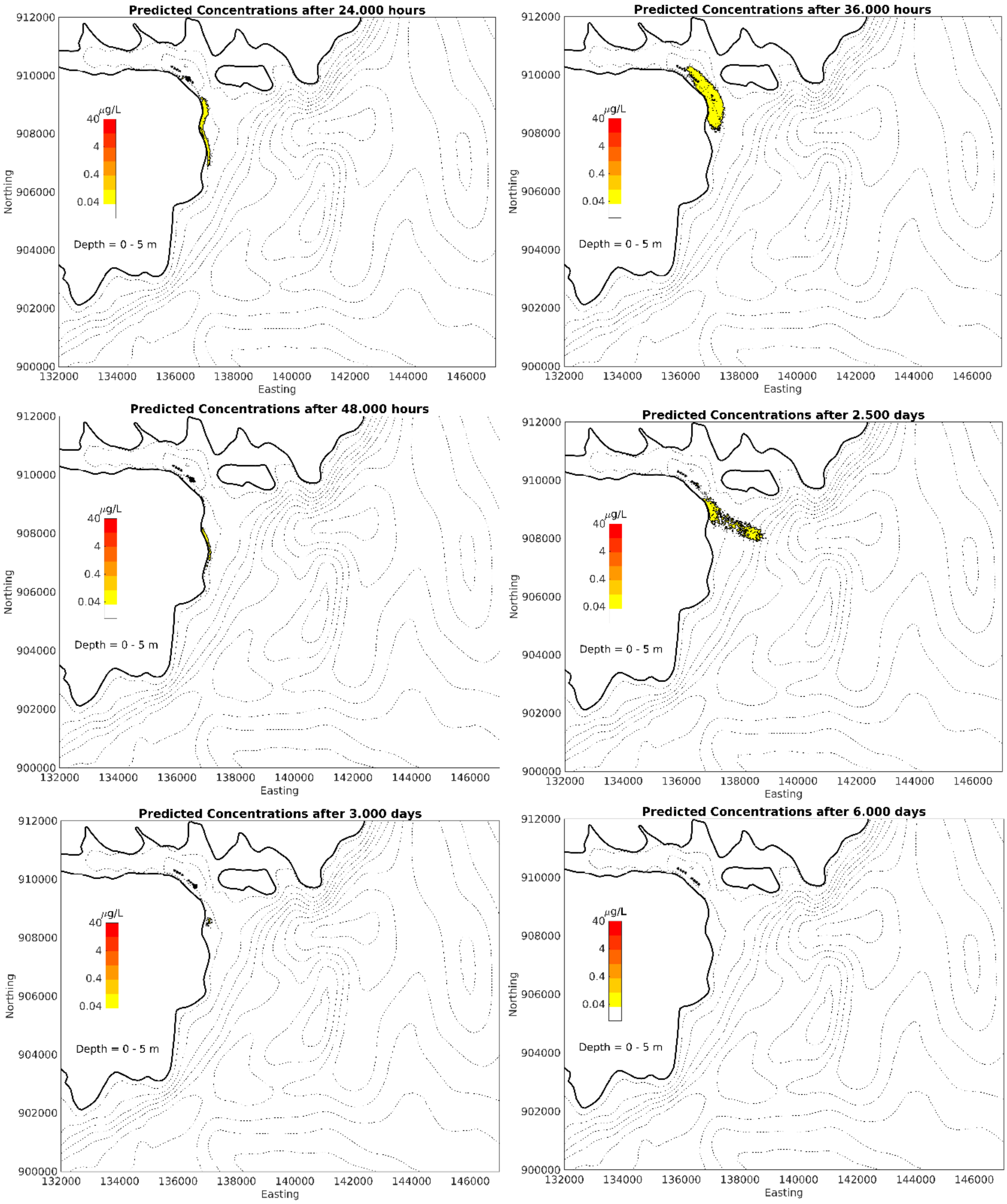

Figure 9. Predicted concentration fields (µg L^{-1}) for a dispersion simulation at neap tides (Run 1) after 24 hours (top left), 36 hours (top right), 48 hours (middle left), 60 hours (2.5 days, middle right), 72 hours (3 days, bottom left) and 144 hours (6 days, bottom right). Pen locations for the Caolas a Deas East and West sites are indicated (○).

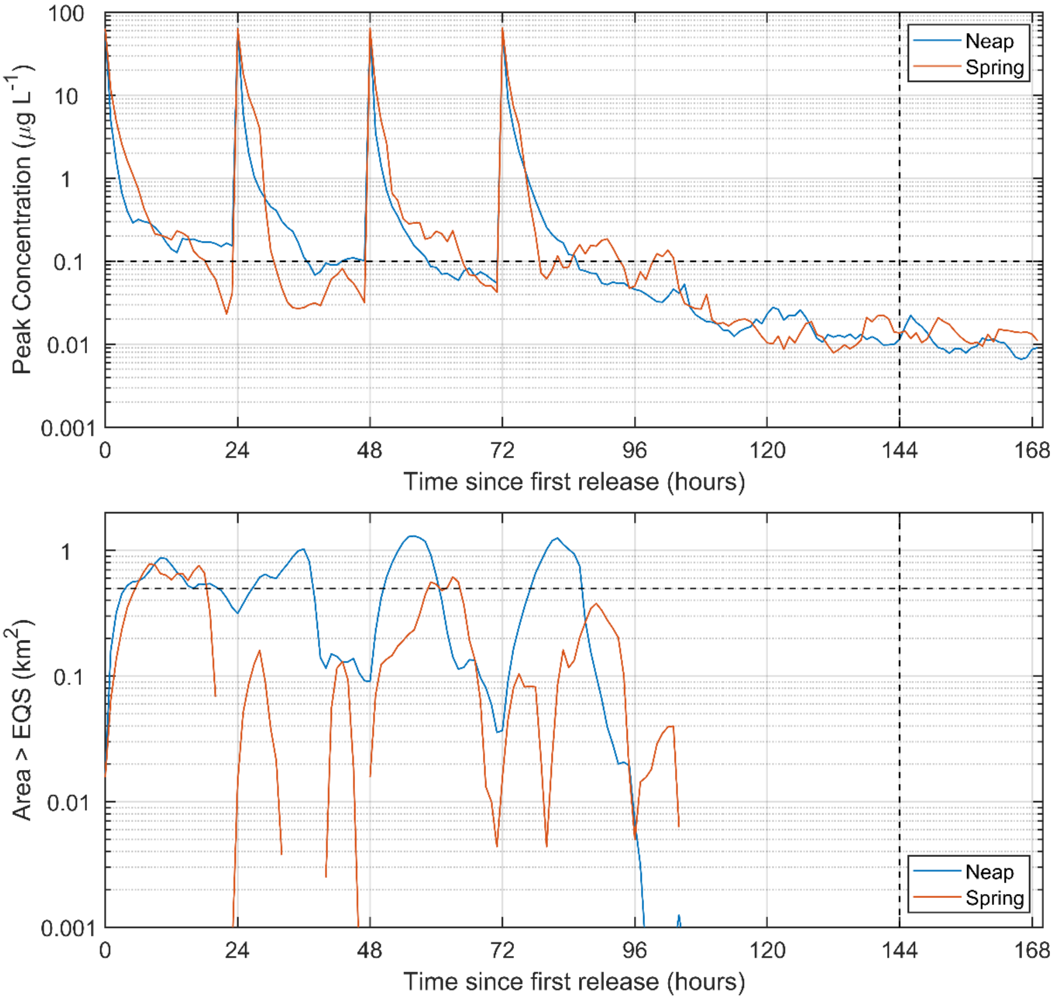

Figure 10. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the baseline neap and spring tide model runs (Runs 1 and 12, Table 4). The model was run during neap and spring tides in March 2021. The MAC and area limit 72 hours after the final treatment (Time = 144 h, vertical dashed line) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.2 Sensitivity to Diffusion Coefficients

The model results were tested for sensitivity to the horizontal and vertical diffusion coefficients used. Although the diffusion coefficient used (K_H = 0.1 m^2 s^{-1}) is thought to be reasonably conservative, the diffusion coefficients estimated from individual transects through dye patches at Loch Shell varied widely. Simulations were therefore performed with lower and higher values of K_H, specifically K_H = 0.05 m^2 s^{-1} and K_H = 0.15 m^2 s^{-1} (Table 4).

The time series of maximum concentration and area exceeding the EQS are shown in Figure 11. The time series confirm that the MAC was not exceeded after 144 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. In the later stages of the simulated dispersion, the peak concentrations were not particularly sensitive to the value of the horizontal diffusion coefficient; this is because, as the patch size increases, dispersion is dominated by shear dispersion and horizontal velocity shearing rather than by eddy diffusion.

Similarly, sensitivity to the vertical diffusion coefficient, K_V, was tested. The model was slightly more sensitive to the vertical diffusion than the horizontal diffusion, but even with increased vertical diffusion, likely in the presence of wind and/or waves, the MAC and EQS conditions were very comfortably met (Figure 11).

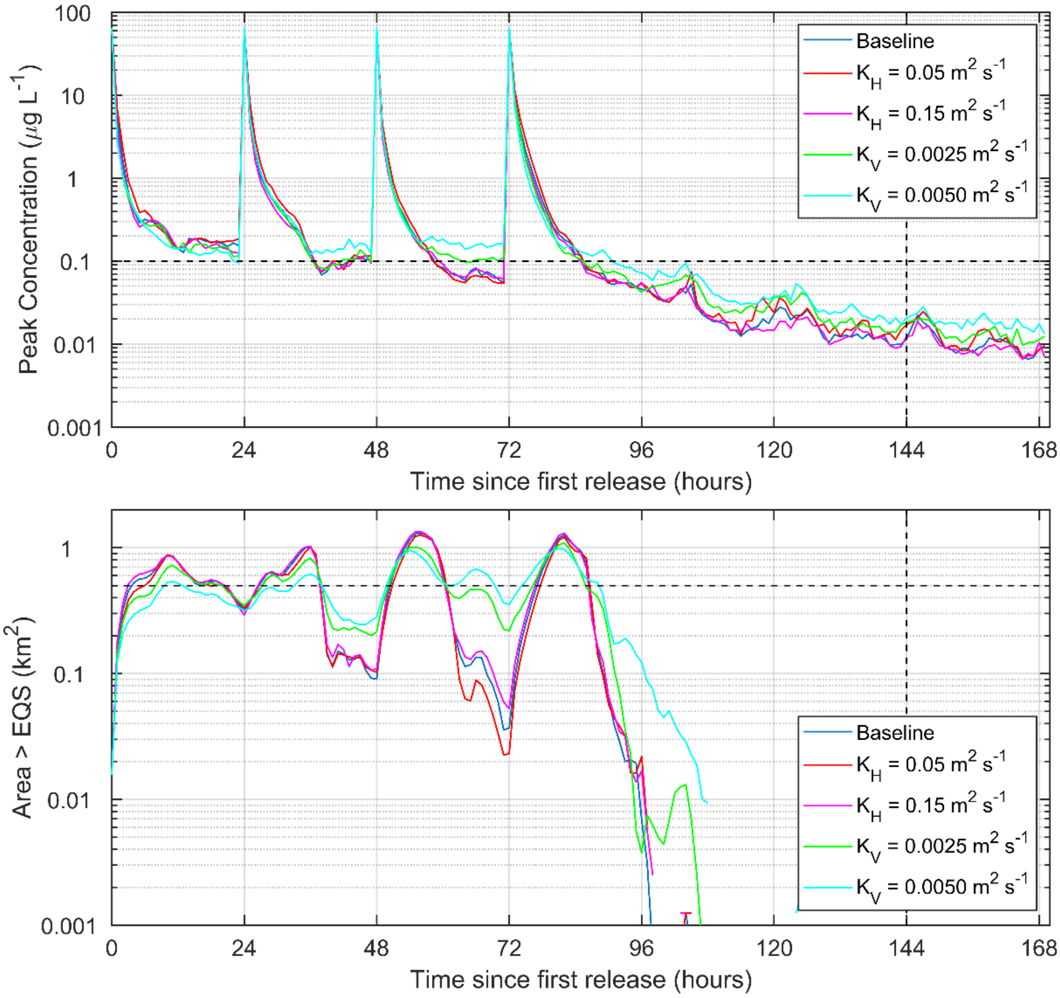

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tide with varying horizontal (K_H) and vertical (K_V) diffusion coefficients. The baseline had K_H = 0.1 m^2 s^{-1} and K_V = 0.001 m^2 s^{-1}. The MAC and area limit 72 hours after the final treatment (Time = 144 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 simulations were repeated with the time of the releases varied by up to ±6 hours (Runs 6 – 11, Table 4), the purpose being to assess the influence, if any, of the state of the tide on subsequent dispersion. The results show a little variability (Figure 12); however, in no case was the MAC exceeded after 144 hours, and the area where the EQS of 0.04 µg L^{-1} was exceeded fell below the limit of 0.5 km^2 within 24 hours of the final treatment. By 72 hours after the final treatment (time = 144 hours), the maximum concentration was less than 0.04 µg L^{-1}.

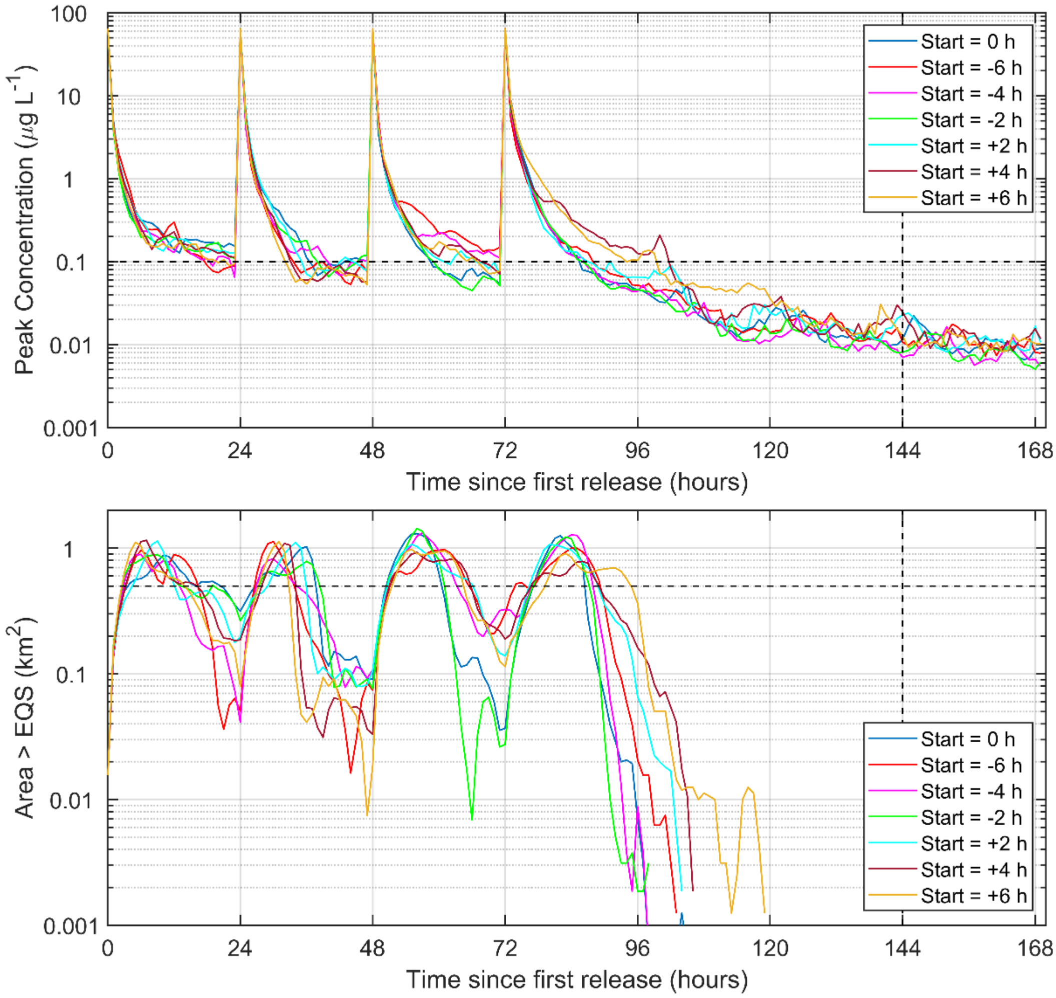

Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 144 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, March 2021 (ID367)

Dispersion simulations were carried out during modelled spring tides in March 2021 (Figure 5), repeating the main set carried out for neap tides (Table 4). The same treatment scenario of one treatment per day, with each treatment being 0.917 kg of azamethiphos, was used. The baseline spring tide simulation results are shown in Figure 10. The peak concentration comfortably meets the MAC after 144 hours, and the area exceeding the EQS is an order of magnitude less than the allowable limit of 0.5 km^2. For all treatment start times, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved (Figure 13 and Figure 14).

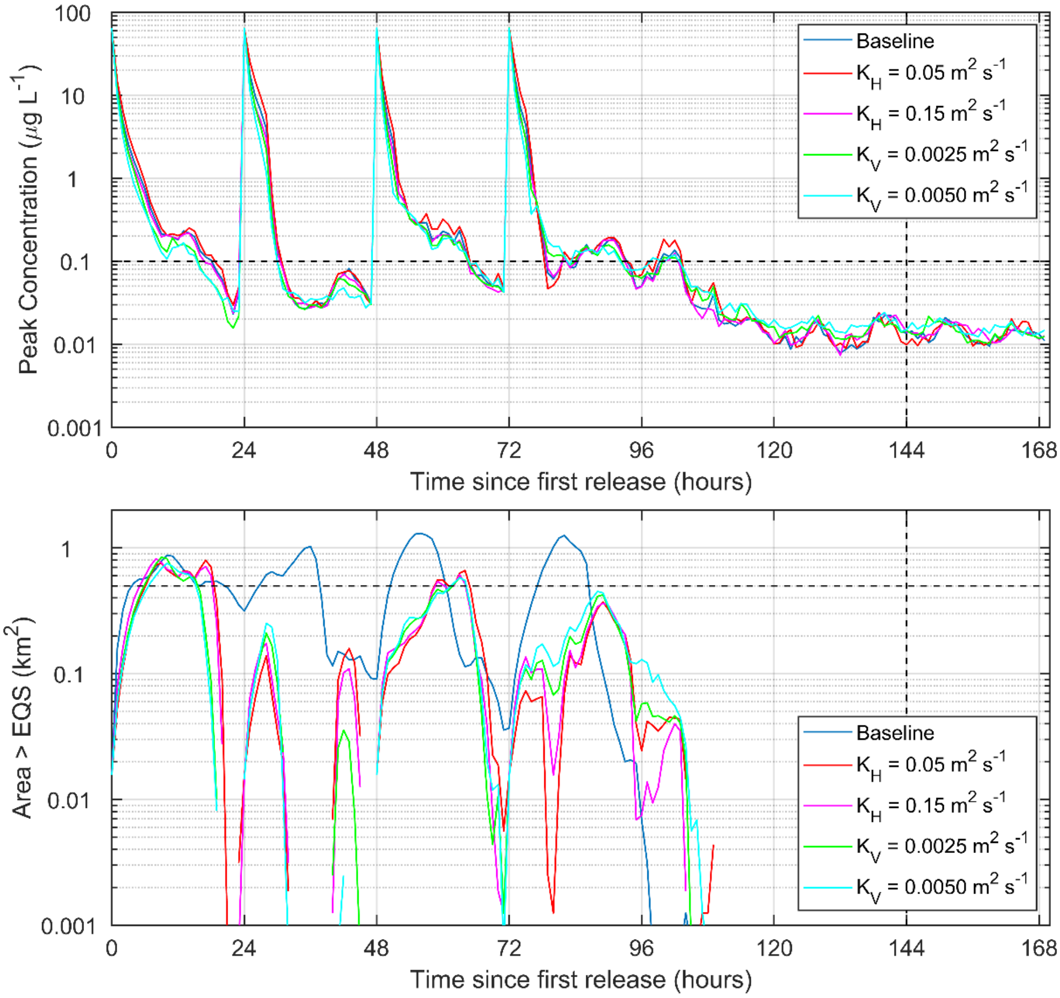

Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during spring tide with varying horizontal diffusion coefficient K_H and vertical diffusion coefficient K_V. The baseline had K_H = 0.1 m^2 s^{-1} and K_V = 0.001 m^2 s^{-1}. The MAC and area limit 72 hours after the final treatment (Time = 144 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

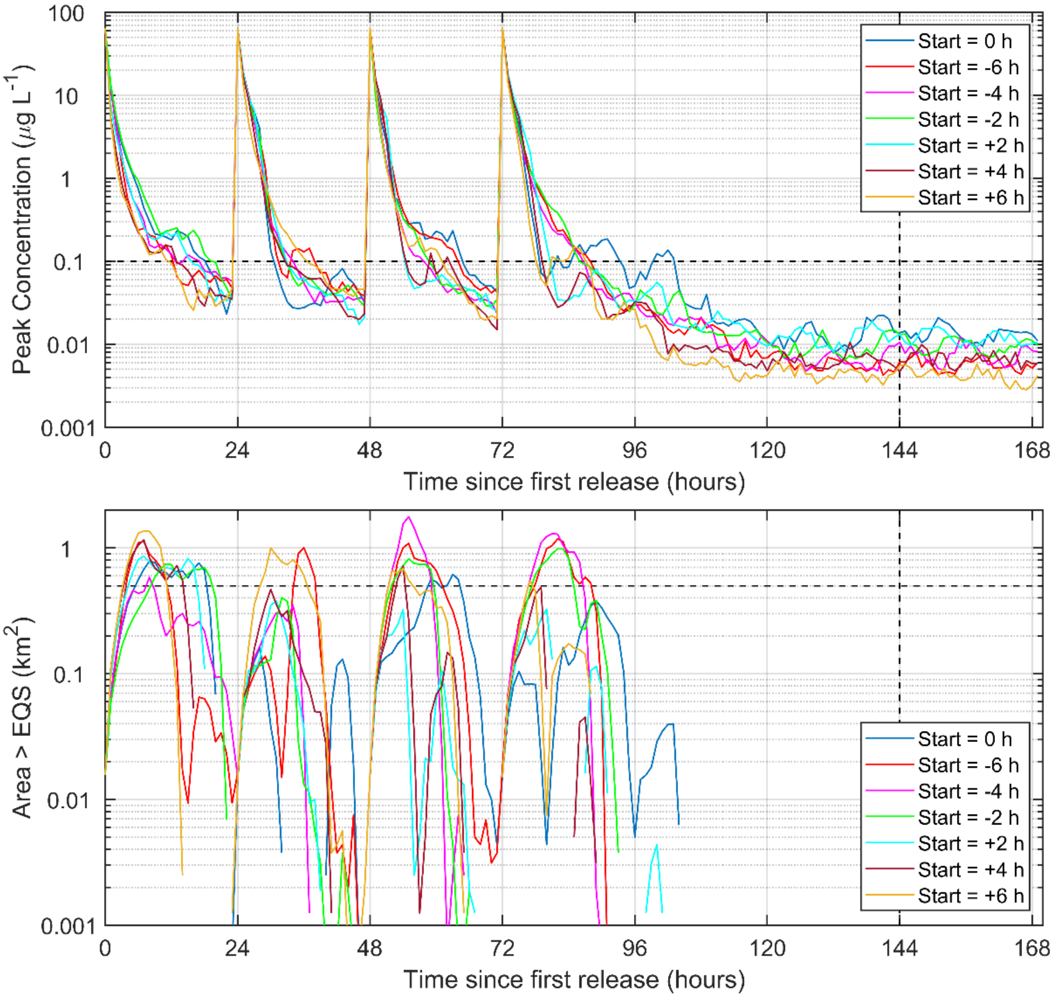

Figure 14. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth set of model runs (Table 4). The model was run at spring tides with varying release times relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 144 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, November 2023 (ID424)

A further set of dispersion simulations was carried out for modelled neap tides in November 2023 (Figure 6, Table 4). The same treatment scenario of one treatment per day, with each treatment being 0.917 kg of azamethiphos, was used. For all horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved (Figure 15). These simulations demonstrate again that the modelled treatment regime will comfortably meet the EQS criteria. Due to the minor effect of start times on the previous simulations, start time was not included in the sensitivity study here.

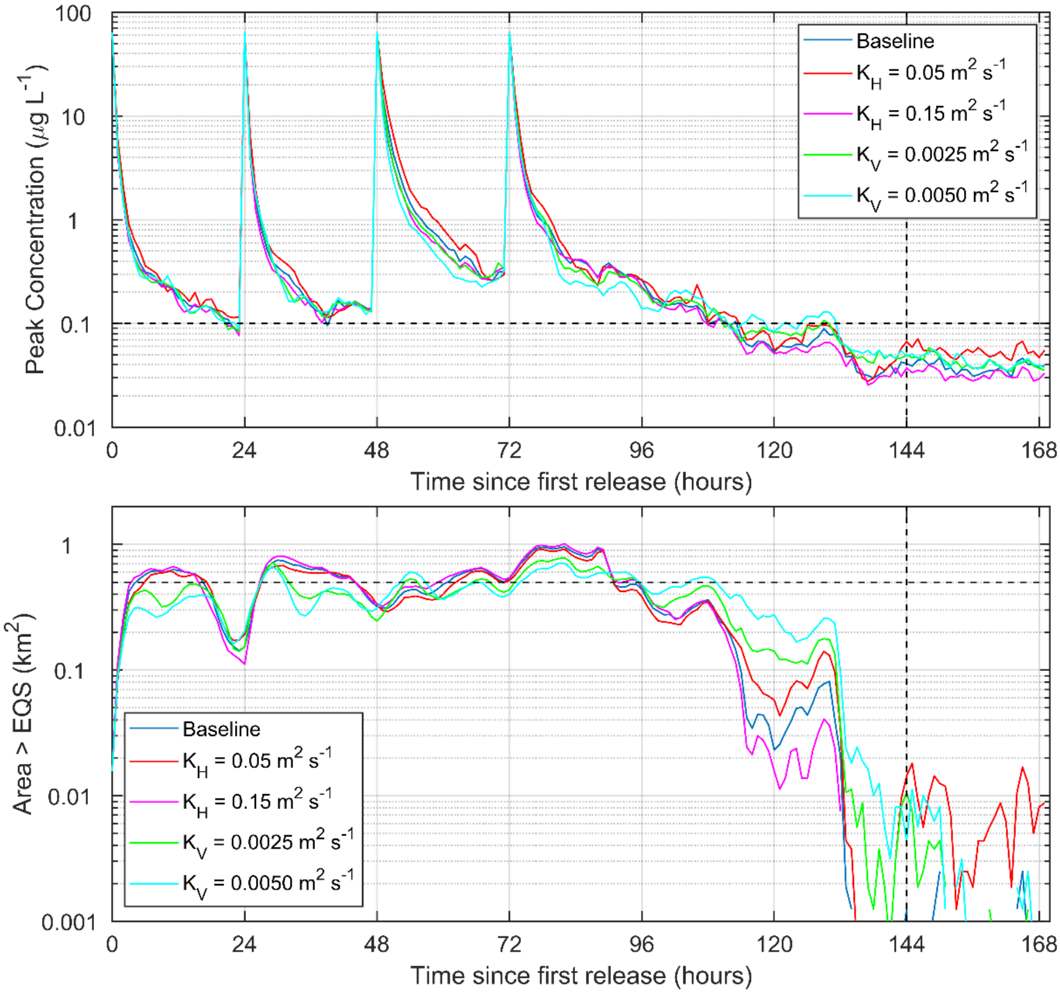

Figure 15. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the sixth set of model runs (varying diffusivity, Table 4). The model was run at neap tides with varying horizontal diffusion coefficient (K_H) and vertical diffusion coefficient (K_V). The baseline had K_H = 0.1 m^2 s^{-1} and K_V = 0.001 m^2 s^{-1}. The MAC and area limit 72 hours after the final treatment (Time = 144 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.6 Dispersion During Spring Tides, October 2023 (ID424)

A final set of 72-hour dispersion simulations was carried out for modelled spring tides in October 2023 (Figure 6, Table 4). The same treatment scenario of one treatment per day, with each treatment being 0.917 kg of azamethiphos, was used. For all 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. Due to the minor effect of start times on the previous simulations, start time was not included in the sensitivity study here.

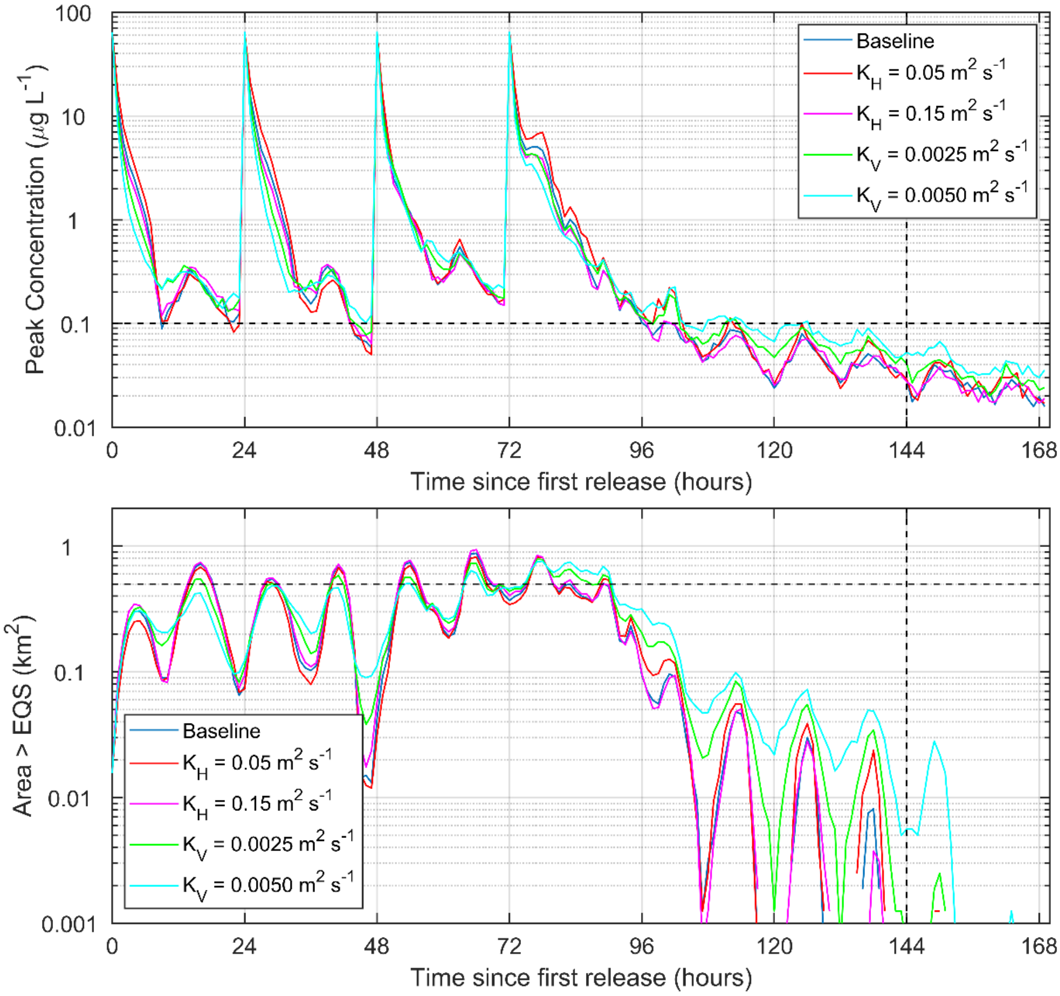

Figure 16. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the seventh set of model runs (varying diffusivity, Table 4). The model was run at spring tides with varying horizontal diffusion coefficient (K_H) and vertical diffusion coefficient (K_V). The baseline had K_H = 0.1 m^2 s^{-1} and K_V = 0.001 m^2 s^{-1}. The MAC and area limit 72 hours after the final treatment (Time = 144 h) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.7 Cumulative Modelling

Results from the cumulative modelling runs, where all eight pens at both Caolas a Deas East and West sites were treated in succession (Table 5 and Table 6) demonstrate that treating both sites sequentially will still comfortably meet the relevant EQS (Figure 17).

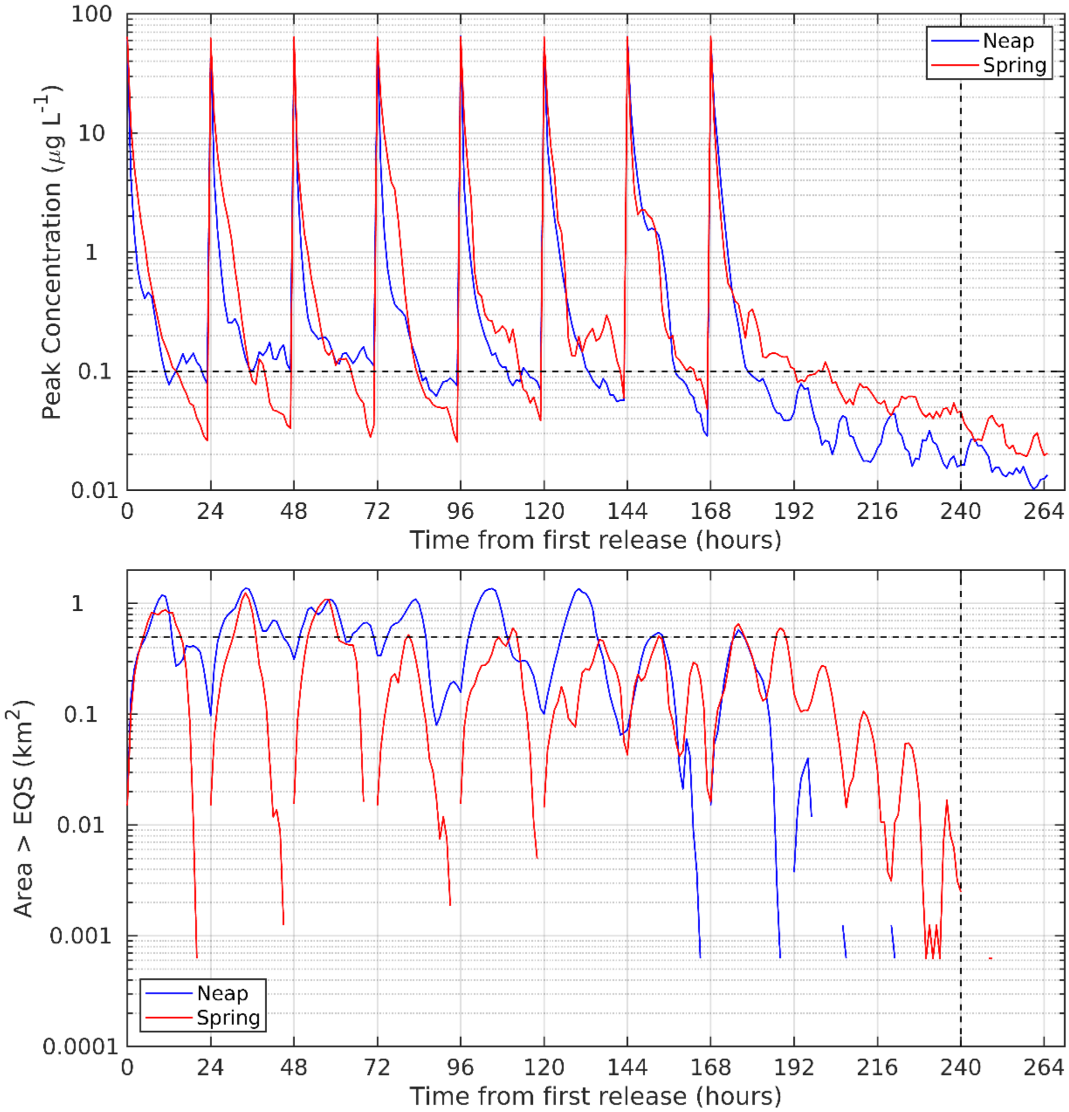

Figure 17. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the cumulative neap and spring tide model runs (Runs 33 and 34, Table 6). The model was run during neap and spring tides in March 2021. The MAC and area limit 72 hours after the final treatment (Time = 240 h, vertical dashed line) of 0.1 µg L^{-1} and 0.5 km^2 are indicated by the horizontal dashed lines.

3.8 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 area, a mean surface current speed of 5.9 cm s^{-1} was used from ID424 (Table 1) which was thought to be a representative value for the surface 0 – 5 m layer at the Caolas a Deas sites. The parameter values used in the calculation of the 3-hour mixing zone ellipse area are shown in Table 7.

The time series of the areas where the 3-hour EQS of 250 ng L^{-1} is exceeded for a pen treatment at neap and spring tides are shown in Figure 18. In both cases, the area exceeding the EQS was less than the allowable mixing zone of 0.093667 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.

This demonstrates that the discharge quantity of 0.917 g of Azamethiphos should not breach the 3-hour EQS.

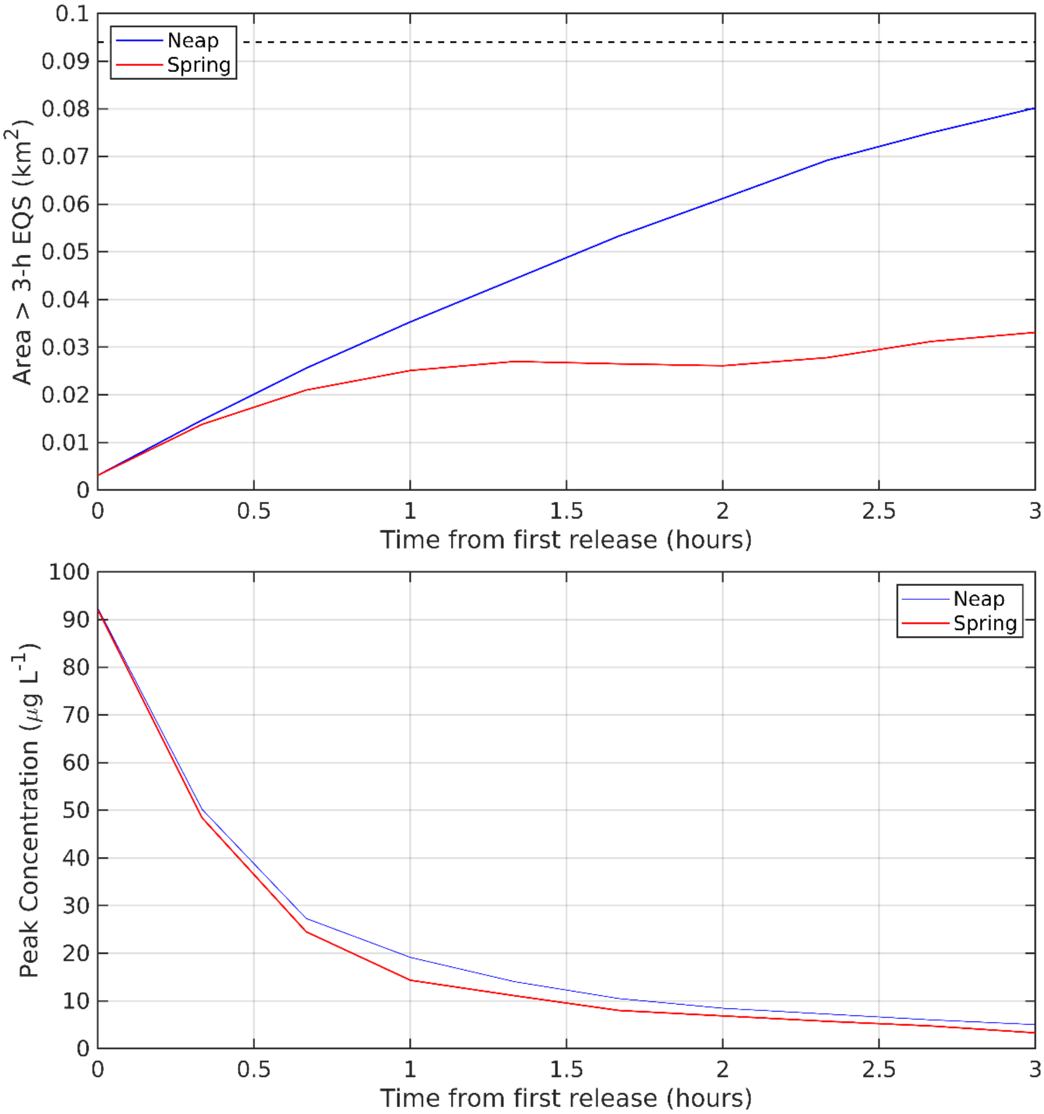

Figure 18. Time series of the area exceeding the 3-hour EQS (top) and peak concentration (bottom) for a pen treatment during the three hours following release at spring and neap tides. The 3-hour mixing zone area is indicated (---).

3.9 Deltamethrin: 6-Hour EQS

The time series of the areas where the 6-hour EQS of 6 ng L^{-1} is exceeded for a pen treatment at neap and spring tides are shown in Figure 19. In both cases, the area exceeding the EQS was less than the allowable mixing zone of 0.264930 km^2 after 6 hours. The peak concentration of 2000 ng L^{-1} decreased to about 50 ng L^{-1} within the 6-hour period.

This demonstrates that the discharge quantity of 0.020 kg of Deltamethrin should not breach the 6-hour EQS.

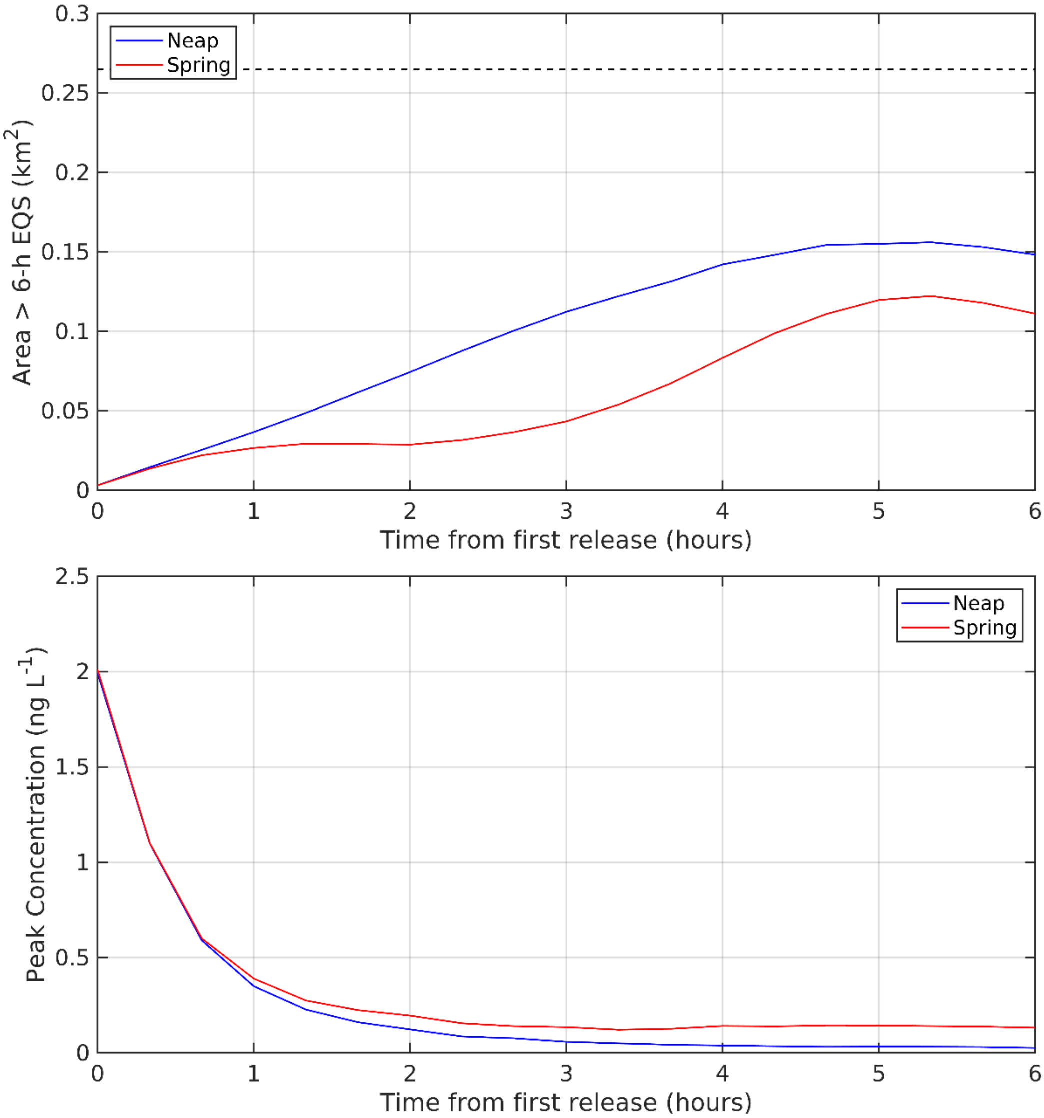

Figure 19. Time series of the area exceeding the 6-hour EQS (top) and peak concentrations of Deltamethrin (bottom) for a pen treatment during the six hours following release at spring and neap tides. The 6-hour mixing zone area is indicated (---).

4 SUMMARY AND CONCLUSIONS

A total of 38 dispersion simulations have been performed to assess whether bath treatments of azamethiphos at the Caolas a Deas East salmon farm in Loch Shell will comply with pertinent environmental quality standards. A realistic treatment regime, with one pen treatment per day, was simulated. Each pen required 0.917 kg of azamethiphos for treatment, resulting in a maximum daily release from the site of 0.917 kg and a total discharge over 3 days of 3.667 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.

The model results confirmed that the treatment scenario proposed will consistently comply with the EQS. The peak concentration during the baseline simulation after 144 hours (72 hours after the final treatment) was consistently 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 some sensitivity testing, the EQS criteria were met. Simulations over two different neap tides from 2021 and 2023 demonstrated that the modelled treatment regime consistently complied with the relevant EQS. For the simulation during spring tides, generally greater dispersion meant that the EQS were met very comfortably. Therefore, we believe that the requested daily quantity of 0.917 kg of azamethiphos can be safely discharged without breaching the EQS.

Table 8. Summary of Results

SITE DETAILS			
Site Name:		Caolas a Deas East	
Site location:		Loch Shell	
Peak biomass (T):		1701	
PEN DETAILS			
Number of pens:		4	
Pen dimensions:		160m Circumference	
Working Depth (m):		20	
Pen group configuration:		1 x 4, 100m matrix	
HYDROGRAPHIC SUMMARY		**ID367**	**ID424**
Near-Surface Currents	Mean Speed (m/s)	0.052	0.059
	Residual Speed (m/s)	0.020	0.018
	Residual Direction (°G)	164	124
	Tidal Amplitude Parallel (m/s)	0.069	0.089
	Tidal Amplitude Normal (m/s)	0.039	0.039
	Major Axis (°G)	145	125
BATH TREATMENTS			
Recommended consent mass – 3-hr Azamethiphos (kg)		0.917	
Recommended consent mass – 24-hr Azamethiphos (kg)		0.917	
Recommended consent mass – 6-hr Deltamethrin (kg)		0.020	

The requested 24-hour mass is substantially larger than the amount predicted by the standard bath model, BathAuto, but the latter is known to be highly conservative, because it does not account for horizontal shearing and dispersion of medicine patches due to spatially-varying current fields, processes which are known to significantly influence dispersion over times scales greater than a few hours (e.g. Okubo, 1971; Edwards, 2015), as illustrated in Figure 9.

Simulations also demonstrated that 20g of Deltamethrin can be discharged without breaching the 6-hour EQS.

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