



# Azamethiphos Dispersion Modelling North Shore West, Loch Erisort CAR/L/1004085

**Mowi Scotland Limited**  
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**CONTENTS**

	Page
<b>EXECUTIVE SUMMARY</b>	<b>5</b>
<b>1 INTRODUCTION</b>	<b>6</b>
<b>1.1 Site Details</b>	<b>6</b>
<b>2. MODEL DETAILS</b>	<b>7</b>
<b>2.1 Model Selection</b>	<b>7</b>
<b>2.2 Model Domain and Boundary Conditions</b>	<b>8</b>
<b>2.3 Medicine Dispersion Modelling</b>	<b>10</b>
<b>2.4 Medicine Dispersion Simulations</b>	<b>12</b>
<b>2.5 3-hour EQS</b>	<b>13</b>
<b>2.6 Interactions with Special Features</b>	<b>14</b>
<b>2.7 Diffusion Coefficients</b>	<b>15</b>
<b>3 RESULTS</b>	<b>17</b>
<b>3.1 Dispersion During Neap Tides, March 2018 (ID194)</b>	<b>17</b>
<b>3.2 Sensitivity to Half-Life</b>	<b>19</b>
<b>3.3 Sensitivity to Diffusion Coefficients</b>	<b>19</b>
<b>3.4 Sensitivity to Release Time</b>	<b>21</b>
<b>3.5 Dispersion during Spring Tides, March 2018 (ID194)</b>	<b>22</b>
<b>3.6 Dispersion During Neap Tides, May 2018 (ID218 &amp; ID219)</b>	<b>23</b>
<b>3.7 3-Hour EQS</b>	<b>24</b>
<b>3.8 Interactions with Special Features</b>	<b>26</b>
<b>4 SUMMARY AND CONCLUSIONS</b>	<b>29</b>
<b>5 REFERENCES</b>	<b>31</b>

## List of Figures

Figure 1. Location of the two salmon farms, North Shore West (left group) and the neighbouring site North Shore East (right group) and the location of the ADCP deployments (▲) relative to the pen positions (o).....	6
Figure 2. The mesh and domain of the modelling study, adapted from the ECLH sub-model.	8
Figure 3. The unstructured mesh around the North Shore sites in the modified model grid, with the pen locations indicated (●), North Shore West (left group) and North Shore East (right group).....	9
Figure 4. Model water depths (m) around the North Shore salmon farms from the modified model. The pen locations indicated (●), North Shore West (left group) and North Shore East (right group).....	9
Figure 5. Sea surface height (SSH) at North Shore from 27 <sup>th</sup> February – 1 <sup>st</sup> May 2018 (ID194). Dispersion simulations were performed over periods of neap tides (blue, start day 4 <sup>th</sup> March 2018) and spring tides (red, start day 26 <sup>th</sup> March 2018) .....	11
Figure 6. Sea surface height (SSH) at North Shore from 2 <sup>nd</sup> May 2018 – 12 <sup>th</sup> July 2018 (ID218 & ID219). Dispersion simulations were performed over periods of neap tides (green, start day 2 <sup>nd</sup> May 2018).....	11
Figure 7. Identified Shellfish Growing and Protected Features areas near the North Shore East site. ....	15
Figure 8. Estimated horizontal diffusivity ( $m^2 s^{-1}$ ) from dye release experiments at North Shore East between 21 <sup>st</sup> and 24 <sup>th</sup> July 2020. The mean diffusivity was $0.06 m^2 s^{-1}$ . .....	16
Figure 9. Maximum fluorescence measured following dye releases at a number of Mowi sites in the Outer Hebrides, including neighbouring site North Shore East (NSE). The black line indicates the rate at which the maximum concentration would fall at a fixed horizontal diffusivity of $K_H = 0.1 m^2 s^{-1}$ ; maximum concentrations fall quicker (i.e. are below the line) if effective $K_H > 0.1 m^2 s^{-1}$ . .....	17
Figure 10. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 72 hours (top middle), 120 hours (top right), 168 hours (bottom left), 192 hours (bottom middle) and 240 hours (bottom right).....	18
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 = 240 h) of $0.1 \mu g L^{-1}$ and $0.5 km^2$ are indicated by the horizontal dashed lines.....	19

- Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient  $K_H$  ( $m^2 s^{-1}$ ). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of  $0.1 \mu g L^{-1}$  and  $0.5 km^2$  are indicated by the horizontal dashed lines.....20
- Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient  $K_V$  ( $m^2 s^{-1}$ ). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of  $0.1 \mu g L^{-1}$  and  $0.5 km^2$  are indicated by the horizontal dashed lines.....21
- 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 = 240 h) of  $0.1 \mu g L^{-1}$  and  $0.5 km^2$  are indicated by the horizontal dashed lines. ....22
- 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  $K_H$  ( $m^2 s^{-1}$ ) and vertical diffusion coefficient  $K_V$  ( $m^2 s^{-1}$ ). The MAC and area limit 72 hours after the final treatment (Time = 168 h) of  $0.1 \mu g L^{-1}$  and  $0.5 km^2$  are indicated by the horizontal dashed lines. ....23
- Figure 16. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, ninth and tenth set of model runs (Table 4). The model was run at neap tides from May 2018 with varying medicine half-life  $T_{1/2}$  (days), horizontal diffusion coefficient  $K_H$  ( $m^2 s^{-1}$ ) and vertical diffusion coefficient  $K_V$  ( $m^2 s^{-1}$ ). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of  $0.1 \mu g L^{-1}$  and  $0.5 km^2$  are indicated by the horizontal dashed lines. ....24
- 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 (---). ....25
- 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 (---). ....26

*Figure 19. Mean and maximum peak concentrations over neap tides for special feature area 1 (top) and special feature area 2 (bottom).....27*

*Figure 20. Proportion of Special Feature Area 2 concentrations above the 72-hour MAC during neap tides.....28*

*Figure 21. Mean and maximum peak concentrations over spring tides for special feature area 1 (top) and special feature area 2 (bottom).....28*

*Figure 22. Proportion of Special Feature Areas concentrations above the 72-hour MAC during spring tides.....29*

**List of Tables**

*Table 1. Summary of Results ..... 5*

*Table 2. Hydrographic Information ..... 7*

*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. ...12*

*Table 4. Dispersion model simulation details for the treatment simulations of 8 pens at North Shore West. ....13*

*Table 5. Parameter values used in the calculation of the 3-hour mixing zone ellipse area and the resulting area.....14*

*Table 6. Summary of Results .....29*

## EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at North Shore West salmon farm will comply with pertinent Environmental Quality Standards (EQS). A realistic treatment regime, with 1 pen treatment per day was simulated. Each pen required 413 g of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) for treatment, resulting in a daily release of 413 g and a total discharge over 7 days of 3.3 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 413 g of azamethiphos should comfortably comply with the EQS. The peak concentration during the baseline simulation 72 hours after the final treatment was less than  $0.1 \mu\text{g L}^{-1}$ , the maximum allowable concentration, and the area where concentrations exceeded the EQS of  $0.04 \mu\text{g L}^{-1}$  was substantially less than the allowable  $0.5 \text{ km}^2$  for both sites. The baseline simulation presented here was designed to be relatively conservative.

The 24-hour mass is substantially larger than the amount predicted by the standard bath model, but the latter is known to be highly conservative, because it does not account for horizontal shearing and dispersion of medicine patches due to spatially-varying current fields, processes which are known to significantly influence dispersion over time scales greater than a few hours.

*Table 1. Summary of Results*

<b>Site Details</b>	
Site Name:	North Shore West
Site Location:	Loch Erisort
Peak Biomass (T):	1,650
<b>Pen Details</b>	
Number of Pens:	8
Pen Circumference (m):	120
Working Depth (m):	9
Pen Group Configuration:	2 x 4
<b>Azamethiphos Consent</b>	
Recommended 3-hour (g):	413
Recommended 24-hour (g):	413



## 1 INTRODUCTION

This report has been prepared by Mowi Scotland Ltd. to meet the requirements of the Scottish Environment Protection Agency (SEPA) for an application to increase the current consent of topical sea lice veterinary medicines at the marine salmon farm North Shore West, Loch Erisort (Figure 1). The report presents results from coupled hydrodynamic and particle tracking modelling to describe the dispersion of bath treatments to determine EQS-compliant quantities for the current site biomass and equipment. The modelling procedure follows, as far as possible, guidance presented by SEPA in January 2022 (SEPA, 2022).



Figure 1. Location of the two salmon farms, North Shore West (left group) and the neighbouring site North Shore East (right group) and the location of the ADCP deployments (▲) relative to the pen positions (○).

### 1.1 Site Details

The site is situated toward the mouth of Loch Erisort, Isle of Lewis (Figure 1). Details of the hydrographic data are provided in Table 2. The receiving water is defined as open water.



Table 2. Hydrographic Information

Hydrographic Data			
	ID194	ID218	ID219
Site:	North Shore West	North Shore West	North Shore East
Current Meter Position:	139060E 922769N	139060E 922769N	139213E 922818N
Depth of Deployment Position (m):	26.53	27.33	28.86
Surface Bin Centre Height Above Bed (m):	20.7	21.72	22.72
Middle Bin Centre Height Above Bed (m):	13.7	13.72	13.72
Bottom Bin Centre Height Above Bed (m):	3.7	3.72	3.72
Duration of Record (days):	62	70	71
Start of Record:	27/02/2018 10:40	02/05/2018 09:00	02/05/2018 08:40
End of Record:	01/05/2018 08:40	12/07/2018 08:20	12/07/2018 08:40
Current Meter Averaging Interval (min):	20	20	20
Magnetic Correction to Grid North:	-4.02	-3.99	-3.98

## 2. MODEL DETAILS

### 2.1 Model Selection

The modelling approach adopted a coupled hydrodynamic and particle tracking method, whereby water currents in the region, modelled using a calibrated hydrodynamic model, advected particles representing the topical medicine around the model domain. Turbulent eddy diffusion was modelled using a random walk method. Outputs from the modelling were derived to assess the dispersion of the medicine following treatments against statutory EQS. The modelling approach is described in full in the Hydrodynamic Model Description (Mowi Scotland Ltd, North Shore Hydrodynamic Model Description, June 2023), and is only summarised here.

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

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

For the particle tracking component, Mowi's in-house model UnPTRACK (Gillibrand, 2022) was used. The model used the hydrodynamic flow fields from the RiCOM model simulations. This model has been used previously to simulate sea lice dispersal (Gillibrand & Willis, 2007), the development of a harmful algal bloom (Gillibrand et al., 2016a) and the dispersion of cypermethrin from a fish farm (Willis et al., 2005). The approach for veterinary medicines is the same as for living organisms, except that medicine has no biological behaviour but instead

undergoes chemical decay: the numerical particles in the model represent “droplets” of medicine of known mass, which reduces over time at a rate determined by a specified half-life. Particles are released at pen locations at specified times, according to a treatment schedule. The number of particles combined with their initial mass represents the mass of medicine required to treat a pen. The particles are then subject to advection, from the modelled flow fields, horizontal and vertical diffusion, and chemical decay. Concentrations of medicine can be calculated throughout the simulation and compared with relevant EQS e.g. 72 hours after the final treatment. Here, the dispersion of azamethiphos following treatment scenarios at North Shore West have been modelled to illustrate the quantities of medicine that disperse safely in the environment.

## 2.2 Model Domain and Boundary Conditions

The unstructured mesh used in the model was adapted from the East Coast of Lewis and Harris (ECLH) sub-model mesh of the Scottish Shelf Model (SSM; Marine Scotland, 2016) (Figure 2). Model resolution was enhanced in the Loch Erisort region particularly around the Mowi sites at North Shore East and North Shore West (Figure 3). The spatial resolution of the model varied from 21 m in some inshore waters to 5 km along the open boundary. The model consisted of 74,588 nodes and 141,229 triangular elements. Bathymetry was also taken from the ECLH model Figure 4. Given that topical medicine dispersion occurs in the upper water column, it was not deemed necessary to use highly detailed bathymetry data in the immediate vicinity of the pens.

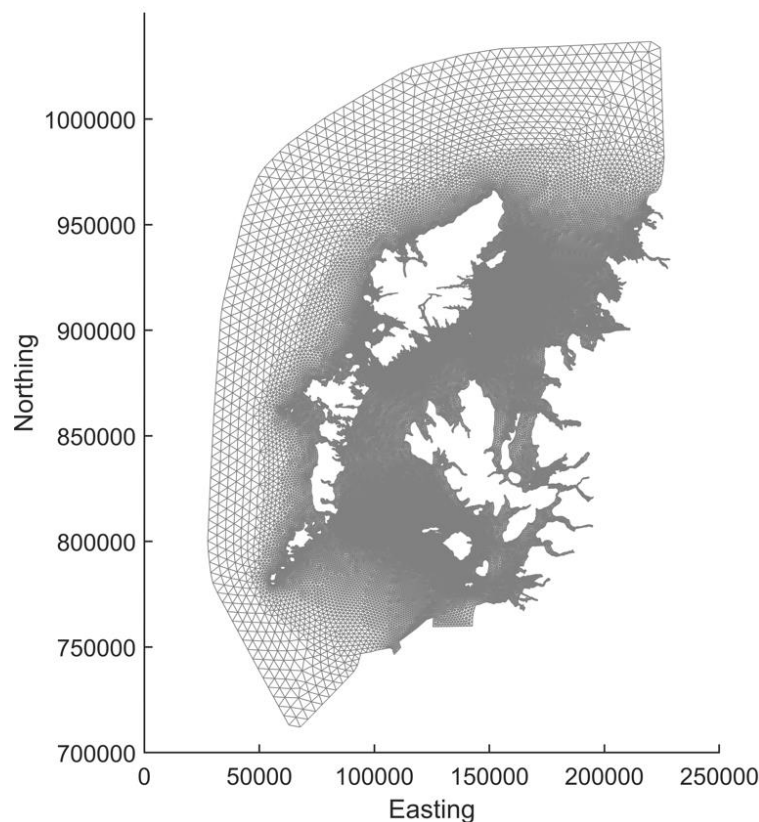


Figure 2. The mesh and domain of the modelling study, adapted from the ECLH sub-model.

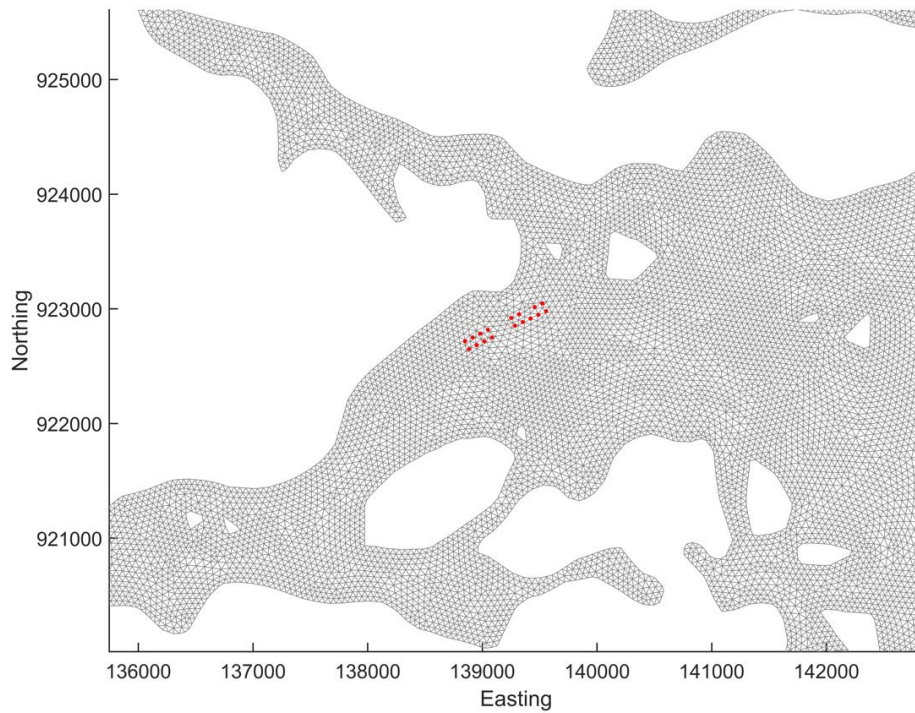


Figure 3. The unstructured mesh around the North Shore sites in the modified model grid, with the pen locations indicated (•), North Shore West (left group) and North Shore East (right group).

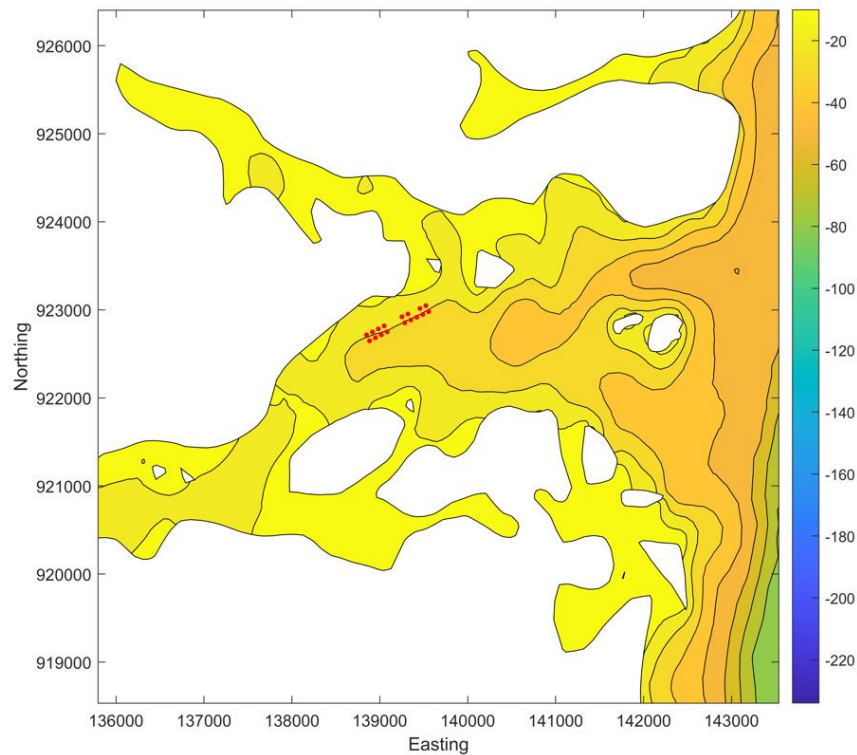


Figure 4. Model water depths (m) around the North Shore salmon farms from the modified model. The pen locations indicated (•), North Shore West (left group) and North Shore East (right group).

The model is forced at the outer boundaries by 8 tidal constituents ( $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ,  $O_1$ ,  $K_1$ ,  $P_1$ ,  $Q_1$ ) 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 North Shore Hydrodynamic Model Description (Mowi Scotland Ltd, 2023).

### 2.3 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the UnPTRACK model (Gillibrand, 2022), simulates the dispersion of patches of medicine discharged from pens following treatment using tarpaulins. The UnPTRACK model uses the same unstructured mesh as the hydrodynamic model, and reads the flow fields directly from the hydrodynamic model output files. Therefore, no spatial or temporal interpolation of the current fields is required, although current velocities are interpolated to particle locations within UnPTRACK. The treatment scenario assumed 1 pen can be treated per day.

To simulate the worst-case scenario, the dispersion modelling was initially conducted using flow fields over a period of 11 days, centred on a small neap tidal range taken from the hydrodynamic model simulations. This is assumed to be the least dispersive set of ambient conditions, when medicine dispersion is least likely to meet the required EQS. Later simulations tested dispersion during spring tides.

A treatment depth of 3 m was chosen as a realistic net depth during application of the medicine for the 120m pens. The initial mass released per pen was calculated from the reduced pen volume and a treatment concentration of  $120 \mu\text{g L}^{-1}$ , with a total mass of 3.3 kg of azamethiphos released during treatment (8 pens). Particles were released from random positions within a pen radius of the centre and within the 0 – 3 m depth range. The simulations used ca. 916,672 numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation for ran for a total of 265 hours (11.04 days). This covered the treatment period (168 hours), a dispersion period to the EQS assessment 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 50 m x 50 m squares using the same depth range as the treatment depth (i.e. 0 – 3 m). Using a regular grid for counting makes calculating particle concentrations and presenting the results easier, and also provides consistent accuracy and precision in the calculated concentrations across the grid.

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

- (i) The maximum concentration ( $\mu\text{g L}^{-1}$ ) anywhere on the regular grid; and
- (ii) The area ( $\text{km}^2$ ) 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 2018 (ID194) (Figure 5). A further set of simulations was performed over neap tides in 2018 (ID218 and ID219) to confirm the adequacy of dispersion during the weakest tides (Figure 6).

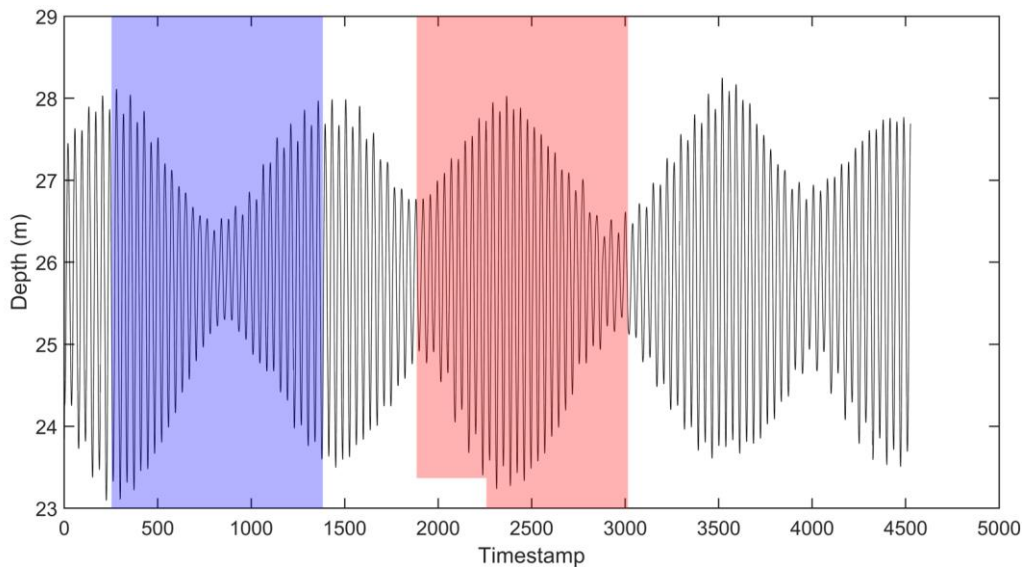


Figure 5. Sea surface height (SSH) at North Shore from 27<sup>th</sup> February – 1<sup>st</sup> May 2018 (ID194). Dispersion simulations were performed over periods of neap tides (blue, start day 4<sup>th</sup> March 2018) and spring tides (red, start day 26<sup>th</sup> March 2018)

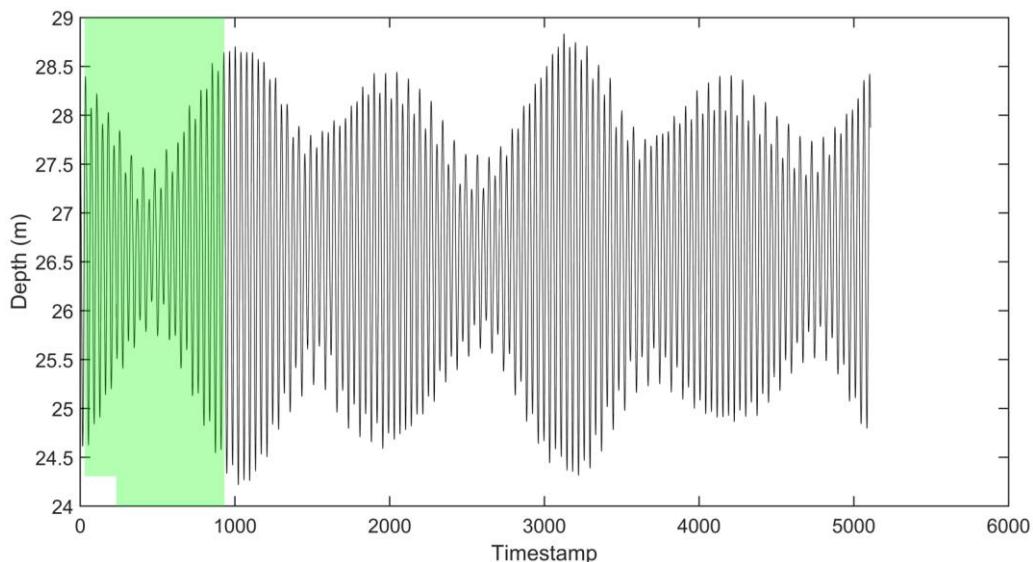


Figure 6. Sea surface height (SSH) at North Shore from 2<sup>nd</sup> May 2018 – 12<sup>th</sup> July 2018 (ID218 & ID219). Dispersion simulations were performed over periods of neap tides (green, start day 2<sup>nd</sup> May 2018).



## 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 (g)	Release Time (hr)
1	138883	922649	3	413	0
2	138950	922683	3	413	24
3	139017	922717	3	413	48
4	139083	922751	3	413	72
5	138849	922716	3	413	96
6	138916	922750	3	413	120
7	138983	922784	3	413	144
8	139049	922818	3	413	168

Table 4. Dispersion model simulation details for the treatment simulations of 8 pens at North Shore West.

Set	Run No.	T <sub>1/2</sub> (h)	K <sub>H</sub>	K <sub>V</sub>	Start Time
Neap Tides, Start day = 5 (4th March 2018, ID194)					
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	0.06	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 = 27 (26th March 2018, ID194)					
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	0.06	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 = 1 (2nd May 2018, ID218 & ID219)					
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	0.06	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 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<sup>-1</sup> 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 9.74 cm s<sup>-1</sup> was used from ID194 (Table 5), this deployment was chosen as it had the slowest surface speed of the two



deployments, for a conservative approach, since both deployments were close-by and hence representative of the site.

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

<b>Parameter</b>	<b>Value</b>
Mean current speed (ms <sup>-1</sup> )	0.097
Area of 120m pen (km <sup>2</sup> )	0.001446
Distance from shore (km)	0.360
Mean water depth (m)	26.53
Treatment Depth (m)	3
<b>Mixing zone ellipse area (km<sup>2</sup>)</b>	<b>0.153588</b>

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<sup>-1</sup> determined. Concentrations from these simulations were calculated on a 10 m x 10 m grid (rather than a 50 m x 50 m grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

## 2.6 Interactions with Special Features

Two near-by Shellfish Growing and Protected Feature areas have been identified (SEPA 2023) (Figure 7) which are thought to be at potential risk from medicine influence and hence must be considered when modelling the treatment releases from North Shore West.

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

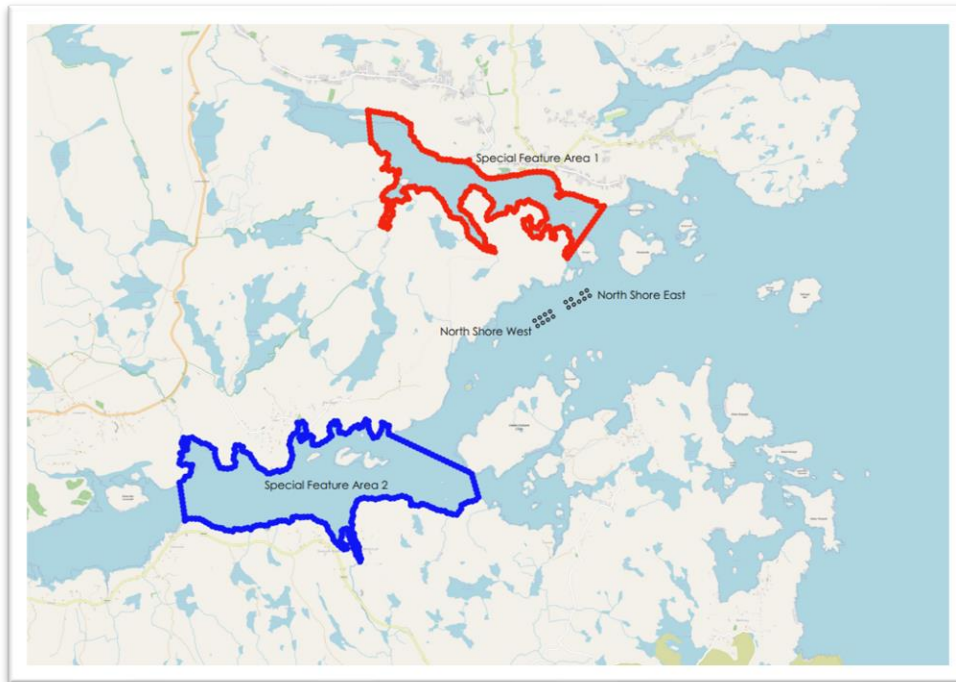


Figure 7. Identified Shellfish Growing and Protected Features areas near the North Shore East site. Special features Area 1 (red), Special Features Area 2 (blue) and specified Shellfish Growing Sites (yellow points).

## 2.7 Diffusion Coefficients

Selection of the horizontal diffusion parameter,  $K_H$ , was guided by dye releases conducted at the neighbouring site North Shore East by Anderson Marine Surveys Ltd between 21<sup>st</sup> and 24<sup>th</sup> July 2020, 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 North Shore East gave a mean horizontal diffusivity of  $0.06 \text{ m}^2 \text{ s}^{-1}$ . 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.

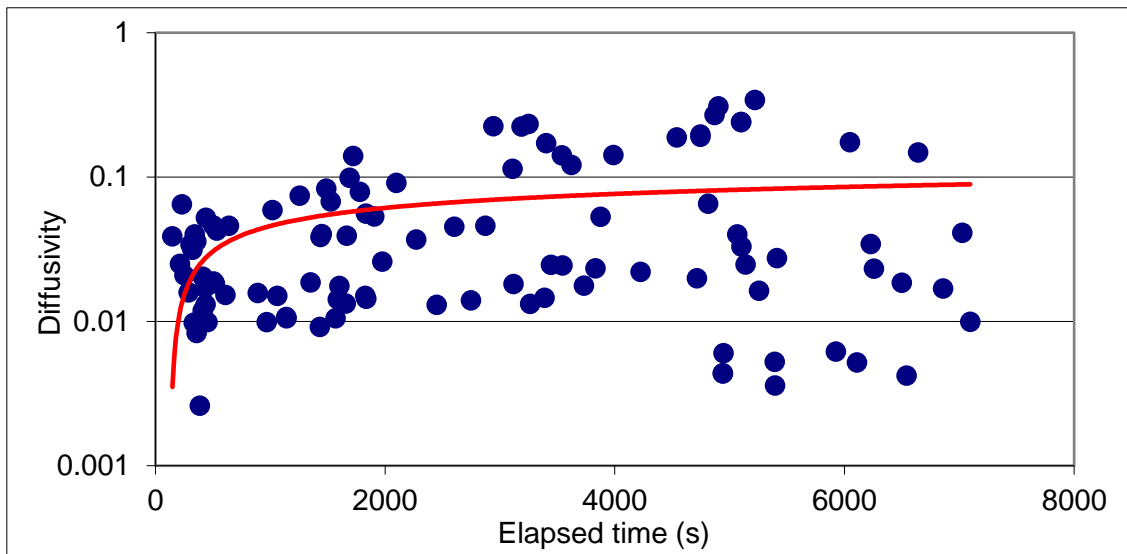


Figure 8. Estimated horizontal diffusivity ( $\text{m}^2 \text{s}^{-1}$ ) from dye release experiments at North Shore East between 21<sup>st</sup> and 24<sup>th</sup> July 2020. The mean diffusivity was  $0.06 \text{ m}^2 \text{ s}^{-1}$ .

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

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

where  $M$  is the mass (kg) of dye released,  $H$  is a depth of water (m) over which the dye is assumed to mix vertically,  $K$  is the horizontal diffusivity ( $\text{m}^2 \text{s}^{-1}$ ), 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 in the Outer Hebrides 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  $\pm 15$  minutes). The results are shown in Figure 9. A nominal mixed depth of  $H = 5 \text{ m}$  was used (see also Dale et al., 2020).

The results support the notion that horizontal diffusivity in the Scottish marine environment is typically greater than  $0.1 \text{ m}^2 \text{ s}^{-1}$ . The observed maximum concentrations, particularly after about 15 minutes (900s), fall faster than a diffusivity of  $0.1 \text{ m}^2 \text{ s}^{-1}$  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  $0.1 \text{ m}^2 \text{ s}^{-1}$ . At periods longer than one hour (3600s), none of the data implied a horizontal diffusivity of less than  $0.3 \text{ m}^2 \text{ s}^{-1}$ . We can conclude that using  $K_H = 0.1 \text{ m}^2 \text{ s}^{-1}$  is a conservative value for modelling bath treatments over periods greater than about 30 minutes.

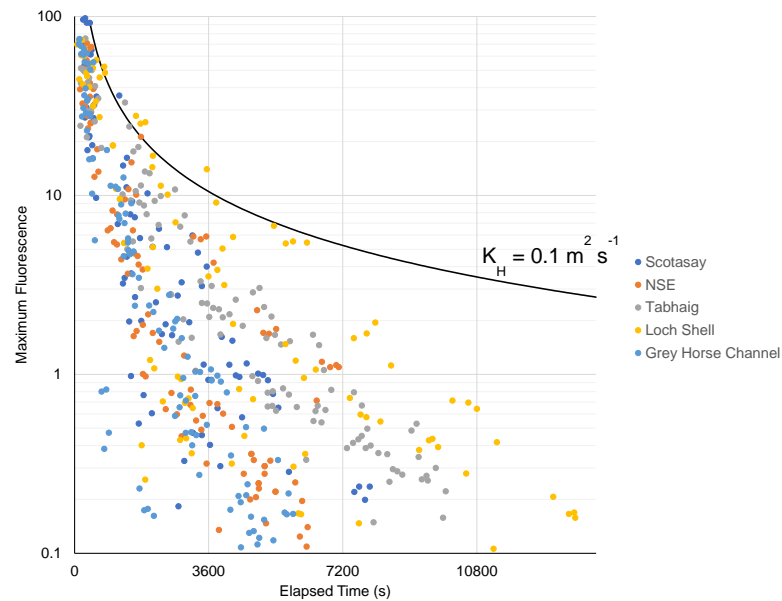


Figure 9. Maximum fluorescence measured following dye releases at a number of Mowi sites in the Outer Hebrides, including neighbouring site North Shore East (NSE). The black line indicates the rate at which the maximum concentration would fall at a fixed horizontal diffusivity of  $K_H = 0.1 \text{ m}^2 \text{ s}^{-1}$ ; maximum concentrations fall quicker (i.e. are below the line) if effective  $K_H > 0.1 \text{ m}^2 \text{ s}^{-1}$ .

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

Most of the simulations described here were conducted using a value of  $K_H = 0.1 \text{ m}^2 \text{ s}^{-1}$ , 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, March 2018 (ID194)

A standard treatment of 8 x 120 m pens, with a reduced net depth of 3 m and assuming 1 pen could be treated per day at a treatment concentration of  $120 \mu\text{g L}^{-1}$ , resulted in a treatment mass per pen of azamethiphos of 413 g, a daily (24-hour) release of the same mass of 413 g and a total treatment release of 3.3 kg over 168 hours. The dispersion of the medicine during and following treatment from Run001 (Table 4) is illustrated in Figure 10. After 24 hours, as the second treatment on day 2 was discharged, discrete patches of medicine are evident from the first treatment release from the first day. The maximum concentration at this time is about  $120 \mu\text{g L}^{-1}$ , due to the release of the second treatment. After 72 hours, as the fourth treatment is discharged, discrete patches of medicine from the previous treatment releases are still evident, but the patches of medicine have rapidly dispersed and are already down to concentrations of the same order as the EQS ( $0.04 \mu\text{g L}^{-1}$ ). The maximum concentration at this time was again approximately  $120 \mu\text{g L}^{-1}$ , due to the release of the fourth treatment.

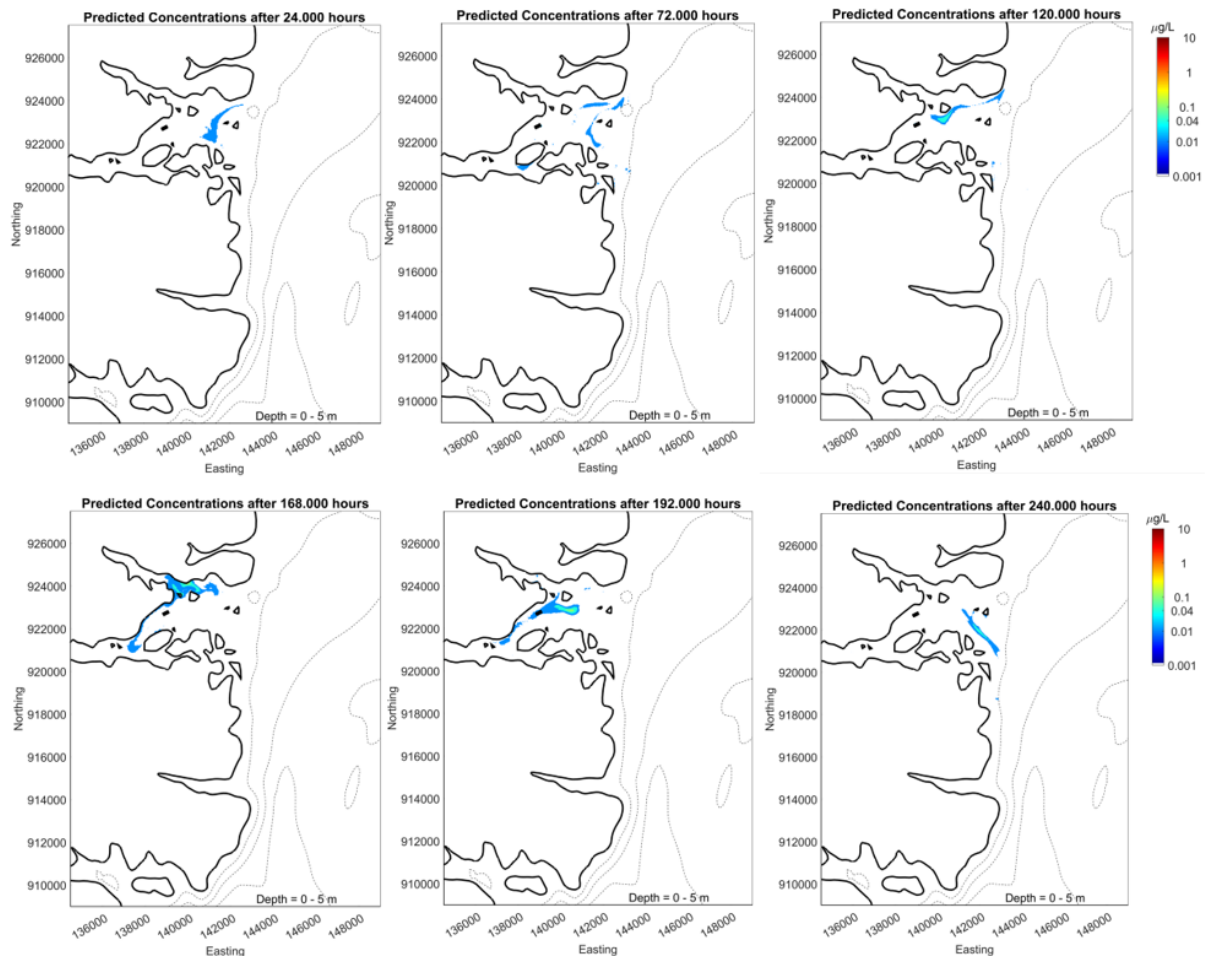


Figure 10. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 72 hours (top middle), 120 hours (top right), 168 hours (bottom left), 192 hours (bottom middle) and 240 hours (bottom right).

The treatment schedule completed after 168 hours (7 days). At this stage, the medicine released on earlier days had already dispersed out into the Minch. It is noticeable that dispersion of the medicine does not happen in a gradual “diffusive” manner, but is largely driven by eddies and horizontal shear in the spatially-varying velocity field, which stretches and distorts the medicine patches and enhances dispersion. Following the final treatment at 168 hours (7 days), the treatment patches were rapidly dispersed and concentrations rapidly fell away below the EQS. Remnants of medicine are seen at the mouth of Loch Erisort but at concentrations below the MAC.

The time series of maximum concentration from this simulation is shown in Figure 11 (blue). The 8 peaks in concentration of  $\sim 120 \mu\text{g L}^{-1}$  following each treatment event over the first 7 days are evident. Following the final treatment after 168 hours, the maximum concentration fell steadily away (Figure 11). A default half-life of 134.4 hours (5.6 days) was used. The maximum concentration seventy-two hours after the final treatment (time = 240 hours) was well below  $0.1 \mu\text{g L}^{-1}$ , the maximum allowable concentration (MAC).

The area where the EQS of  $0.04 \mu\text{g L}^{-1}$  was exceeded peaked at about  $0.5 \text{ km}^2$  just before the final treatment, but had fallen well below the  $0.5 \text{ km}^2$  threshold within 48h of the final treatment; by 72 hours 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  $0.1 \text{ m}^2 \text{ s}^{-1}$ , and a medicine half-life of 134.4 hours, the EQS are comfortably achieved. In the following sections, the sensitivity of the model results to the medicine half-life, diffusion coefficients and tidal state are examined.

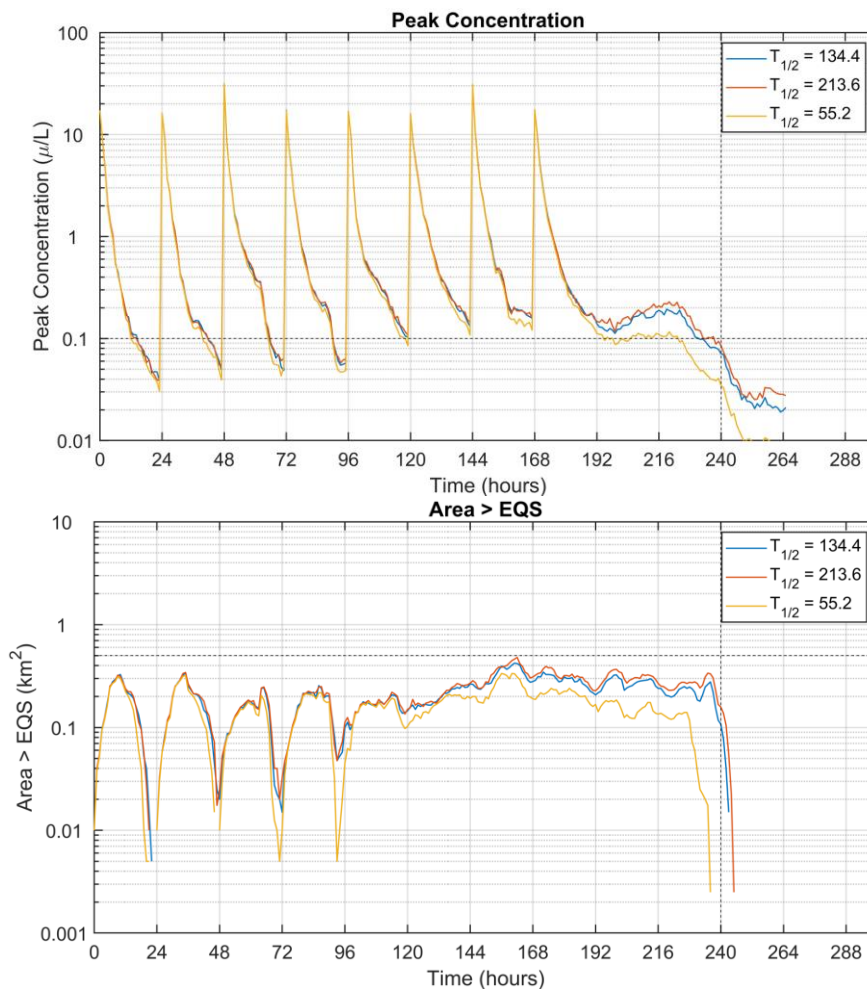


Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tide with varying medicine half-life ( $T_{1/2}$ ). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of  $0.1 \mu\text{g L}^{-1}$  and  $0.5 \text{ km}^2$  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  $0.04 \mu\text{g L}^{-1}$  is exceeded peaked at about  $0.5 \text{ km}^2$  following the second last treatment, but had fallen well below  $0.5 \text{ km}^2$ , for all simulated half-lives, within 72 hours of the final treatment (Figure 11).

### 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  $K_H = 0.1 \text{ m}^2 \text{ s}^{-1}$ . Simulations were also performed with lower and higher values of  $K_H$ , specifically  $K_H = 0.2 \text{ m}^2 \text{ s}^{-1}$  and  $K_H = 0.06 \text{ m}^2 \text{ s}^{-1}$  (Table 4). The time series of maximum concentration and area exceeding the EQS are shown in Figure 12. The time series confirm that the MAC was not exceeded after 240 hours (72 hours after the final treatment) with any of the different horizontal diffusion coefficients. The area limit of  $0.5 \text{ km}^2$  was also comfortably met in all cases.

Similarly, sensitivity to the vertical diffusion coefficient,  $K_V$ , was tested (Figure 13). The model results are not particularly sensitive to the vertical diffusion rate, but increased vertical diffusion, likely in the presence of wind and/or waves, led to slightly smaller areas where the EQS was exceeded.

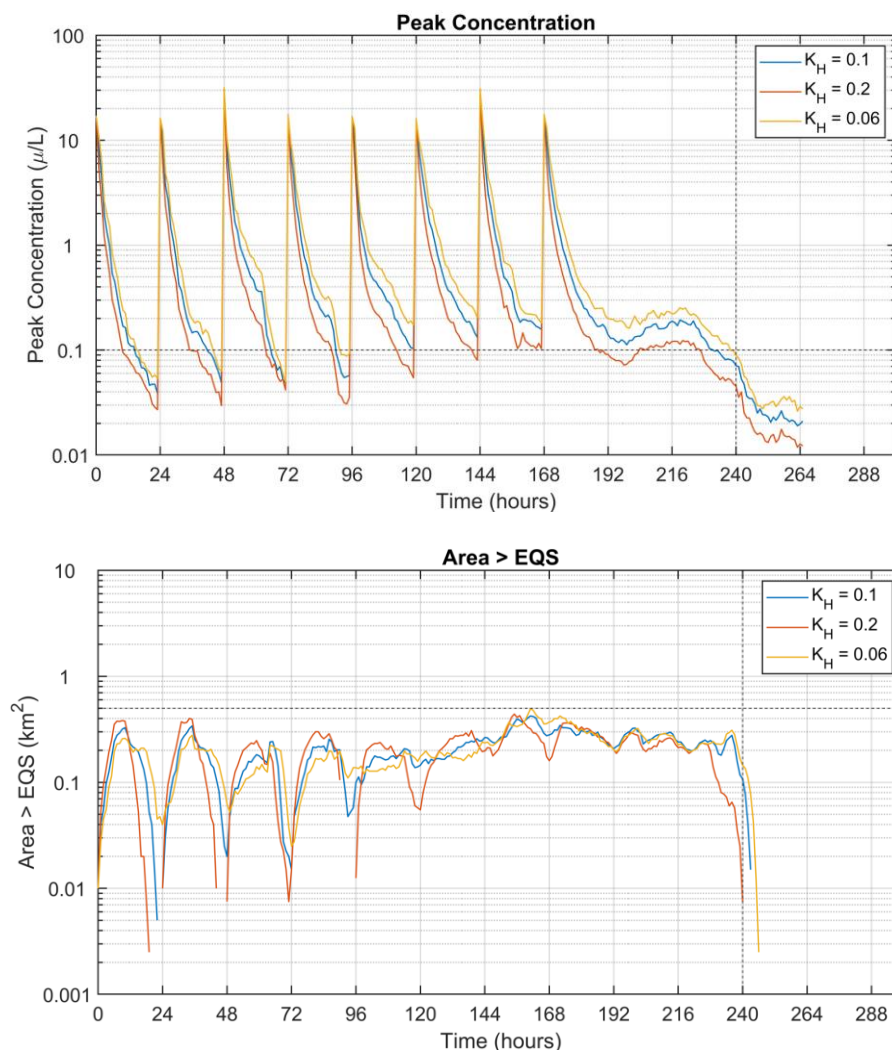


Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient  $K_H$  ( $\text{m}^2 \text{ s}^{-1}$ ). The MAC and area limit 72 hours after the final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



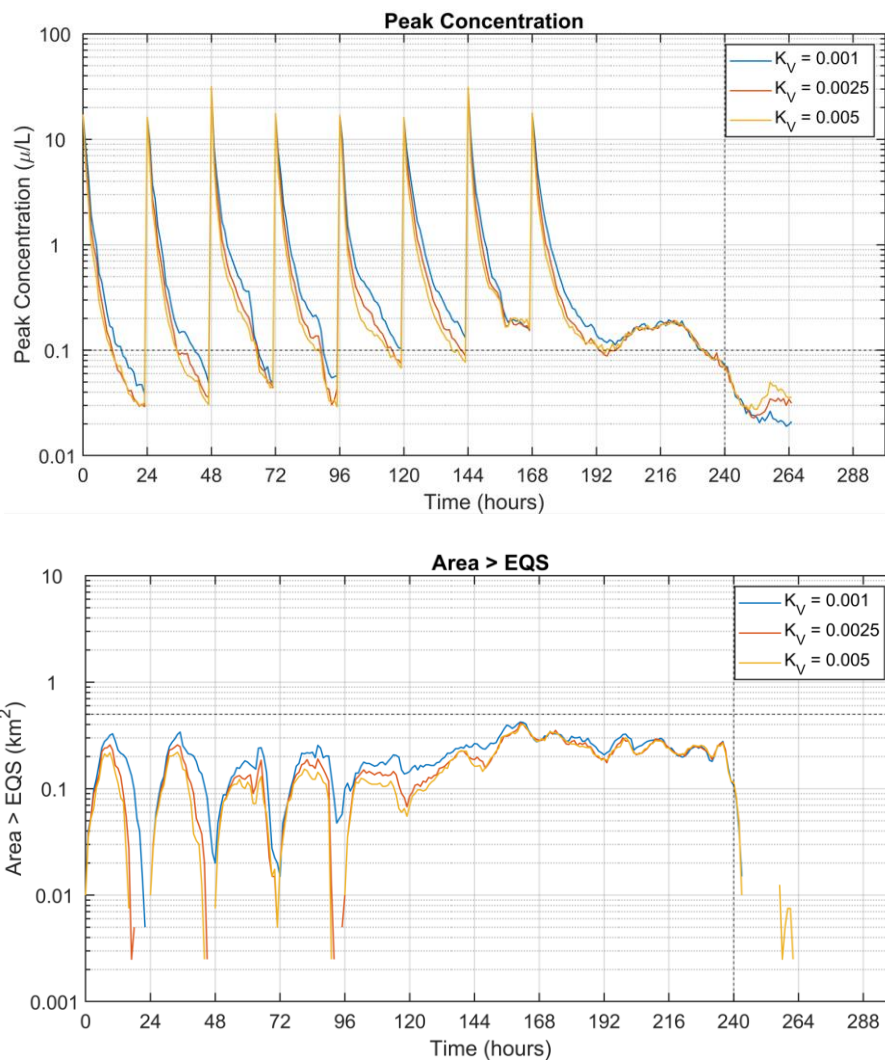


Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient  $K_V$  ( $\text{m}^2 \text{ s}^{-1}$ ). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of  $0.1 \mu\text{g L}^{-1}$  and  $0.5 \text{ km}^2$  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  $\pm 6$  hours, the purpose being to assess the influence, if any, of the state of the tide on subsequent dispersion. The results show some minor variability. A half-life of 134.4 hours was used in these runs which is thought to still be conservative.

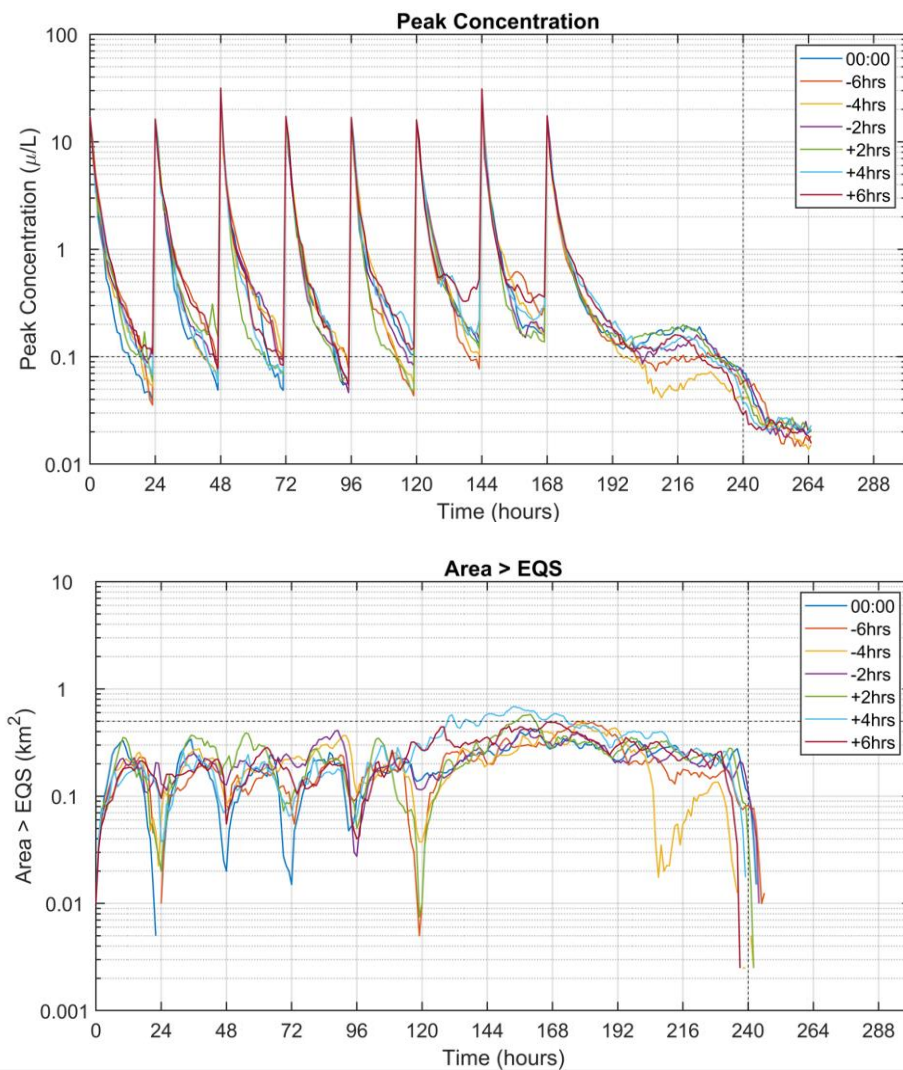


Figure 14. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 240 h) of  $0.1 \mu\text{g L}^{-1}$  and  $0.5 \text{ km}^2$  are indicated by the horizontal dashed lines.

### 3.5 Dispersion during Spring Tides, March 2018 (ID194)

Dispersion simulations were carried out during modelled spring tides in March 2018 (Figure 5), repeating the main set carried out for neap tides (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 413 g of Azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were achieved (Figure 15).

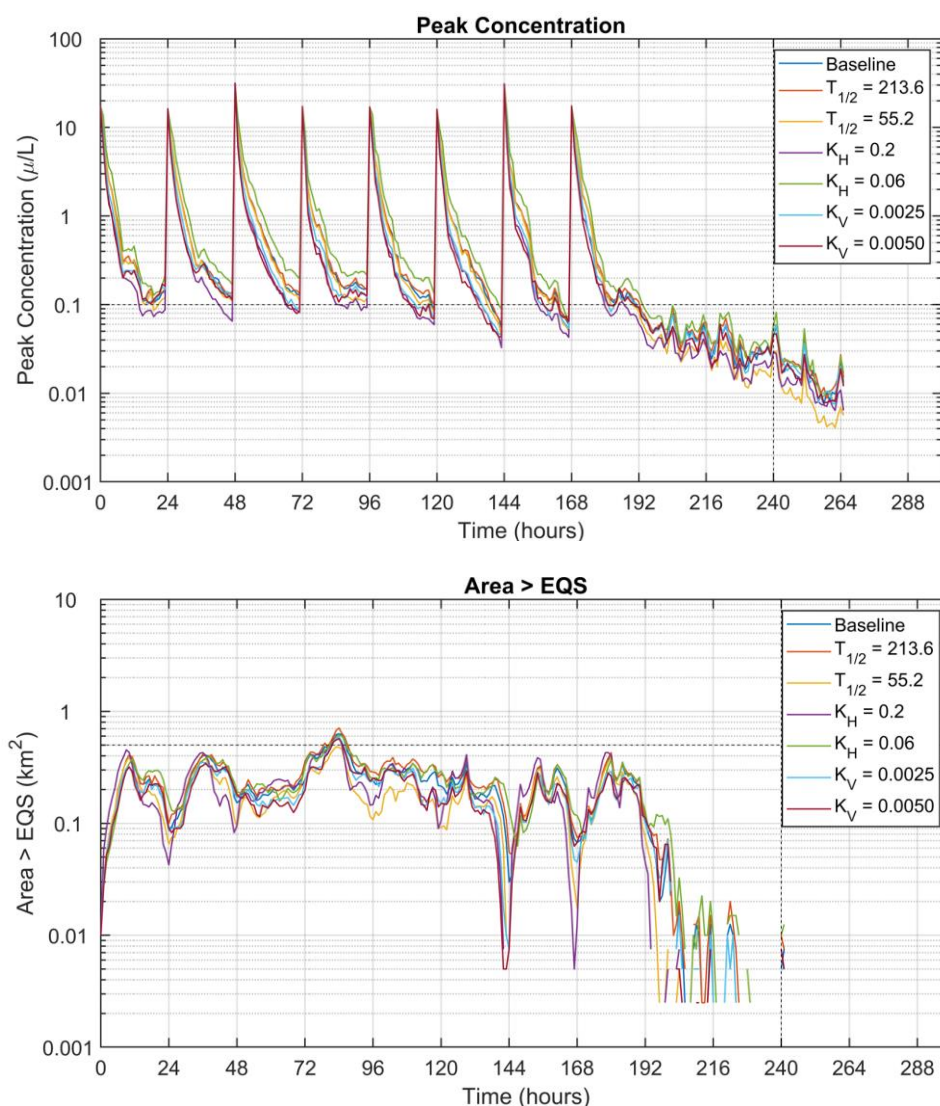


Figure 15. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life  $T_{1/2}$  (days), horizontal diffusion coefficient  $K_H$  ( $m^2 s^{-1}$ ) and vertical diffusion coefficient  $K_V$  ( $m^2 s^{-1}$ ). The MAC and area limit 72 hours after the final treatment (Time = 168 h) of  $0.1 \mu g L^{-1}$  and  $0.5 km^2$  are indicated by the horizontal dashed lines.

### 3.6 Dispersion During Neap Tides, May 2018 (ID218 & ID219)

A further set of dispersion simulations during modelled neap tides in May 2018 were carried out (Figure 6), repeating the main set carried out for neap tides in March 2018 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 413 g of Azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved. These simulations demonstrate again that the modelled treatment regime will comfortably meet the EQS criteria.

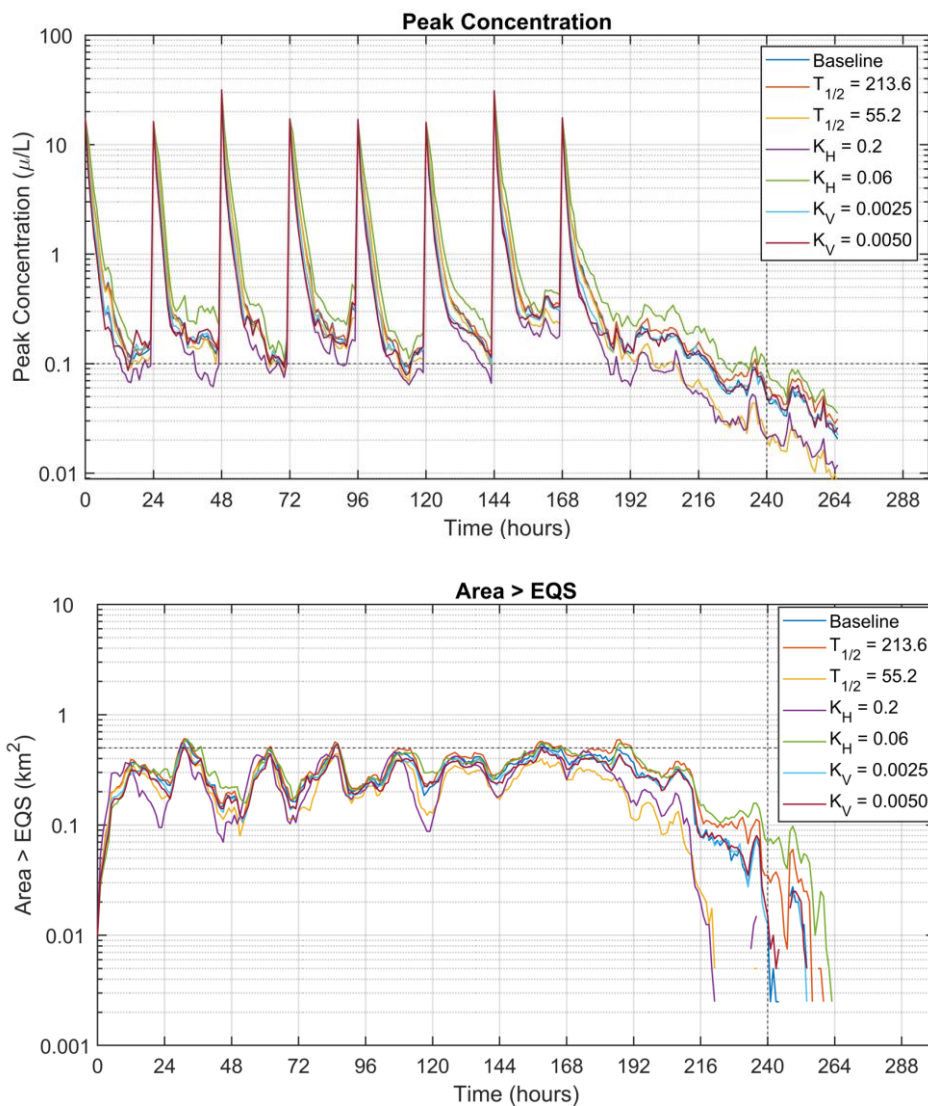


Figure 16. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, ninth and tenth set of model runs (Table 4). The model was run at neap tides from May 2018 with varying medicine half-life  $T_{1/2}$  (days), horizontal diffusion coefficient  $K_H$  ( $m^2 s^{-1}$ ) and vertical diffusion coefficient  $K_V$  ( $m^2 s^{-1}$ ). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of  $0.1 \mu g L^{-1}$  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  $9.7 cm s^{-1}$  was used from ID194 (Table 1) which was thought to be a representative value for the surface 0 – 5 m layer at North Shore. The parameter values used in the calculation of the 3-hour mixing zone ellipse area are shown in Table 5.

The time series of the areas where the 3-hour EQS of  $250 ng L^{-1}$  is exceeded for each individual pen treatment at neap tide (first release on 4<sup>th</sup> March 2018) are shown in Figure 17. For each



treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.1536 km<sup>2</sup>) after 3 hours. The peak concentration of 120 µg L<sup>-1</sup> decreased to less than 10 µg L<sup>-1</sup> within the 3-hour period.

For spring tide releases (first release on 26<sup>th</sup> March 2018), 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 413 g of Azamethiphos from each of the eight 120 m pens at North Shore should not breach the 3-hour EQS.

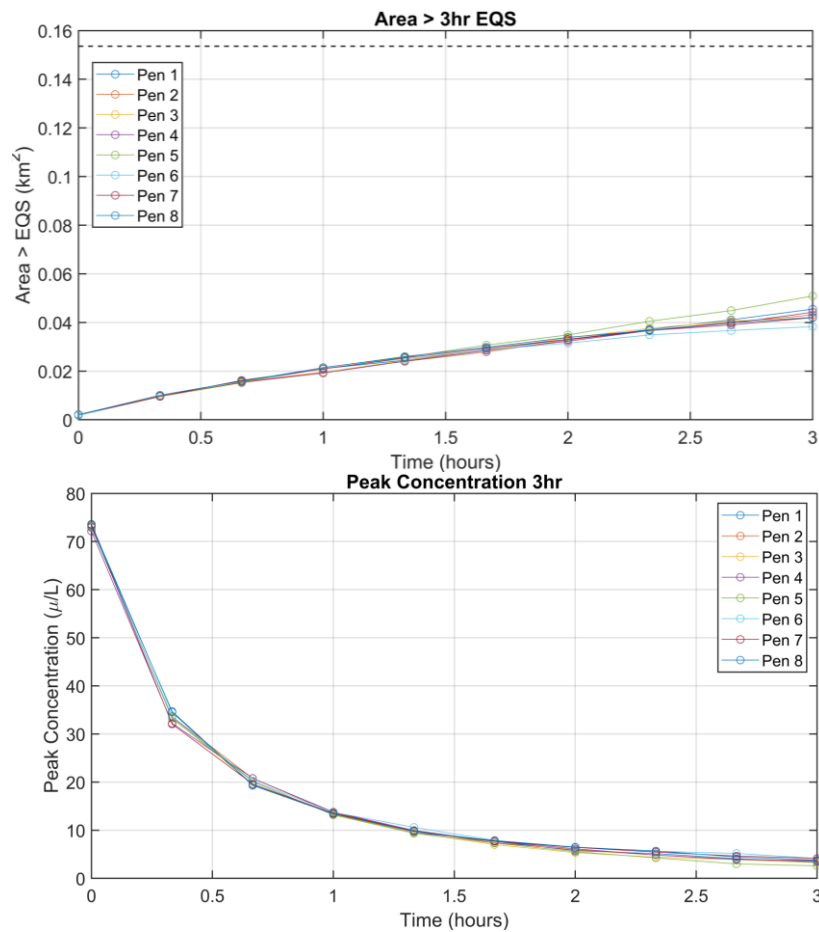


Figure 17. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

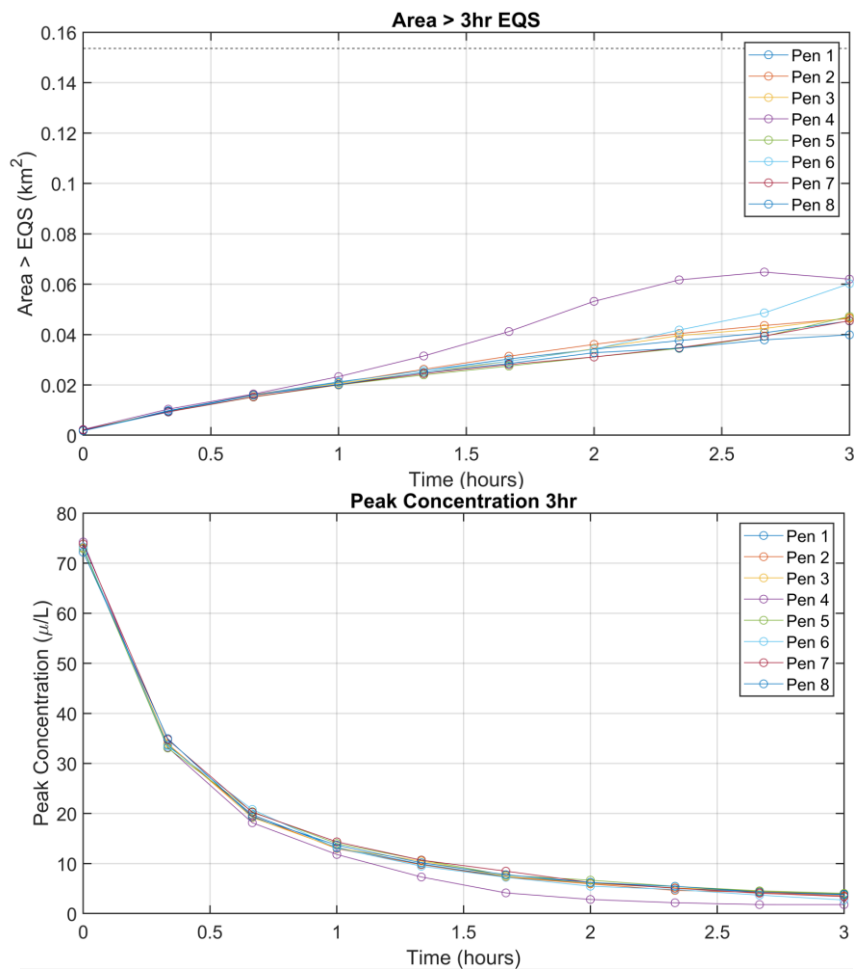


Figure 18. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area indicated (---).

### 3.8 Interactions with Special Features

Figure 19 shows the mean and maximum peak concentrations of Azamethiphos every hour within the two special feature areas at neap tide for a 5 m layer above the seabed following treatment at North Shore West. The concentrations shown during neap tide are minimal with maximum concentrations well below the 3-hour ( $0.25 \mu\text{g L}^{-1}$ ) MAC. The maximum concentrations seen within Special Feature Area 2 breach the 72-hour ( $0.1 \mu\text{g L}^{-1}$ ) MAC at 155 hours but quickly drops below this threshold. Figure 20 shows the proportion of Special Feature Area 2 that breaches the 72-hour MAC throughout the simulation.

Figure 21 shows the mean and maximum peak concentrations of Azamethiphos every hour within the two special feature areas at spring tide for a 5 m layer above the seabed following treatment at North Shore West. The concentrations shown during spring tides are minimal with maximum concentrations well below the 3-hour ( $0.25 \mu\text{g L}^{-1}$ ) MAC. The concentrations breach the 72-hour ( $0.1 \mu\text{g L}^{-1}$ ) MAC at several points throughout the simulation but rapidly fall away after a couple of hours. Figure 22 shows the proportion of the concentrations within the special feature areas which are over the 72-hour MAC. The proportions shown are negligible. These

results indicate that the medicine releases from North Shore West fish farm will not have a detrimental effect on the near-by special feature areas and that medicine concentrations stay at acceptable low levels at all times.

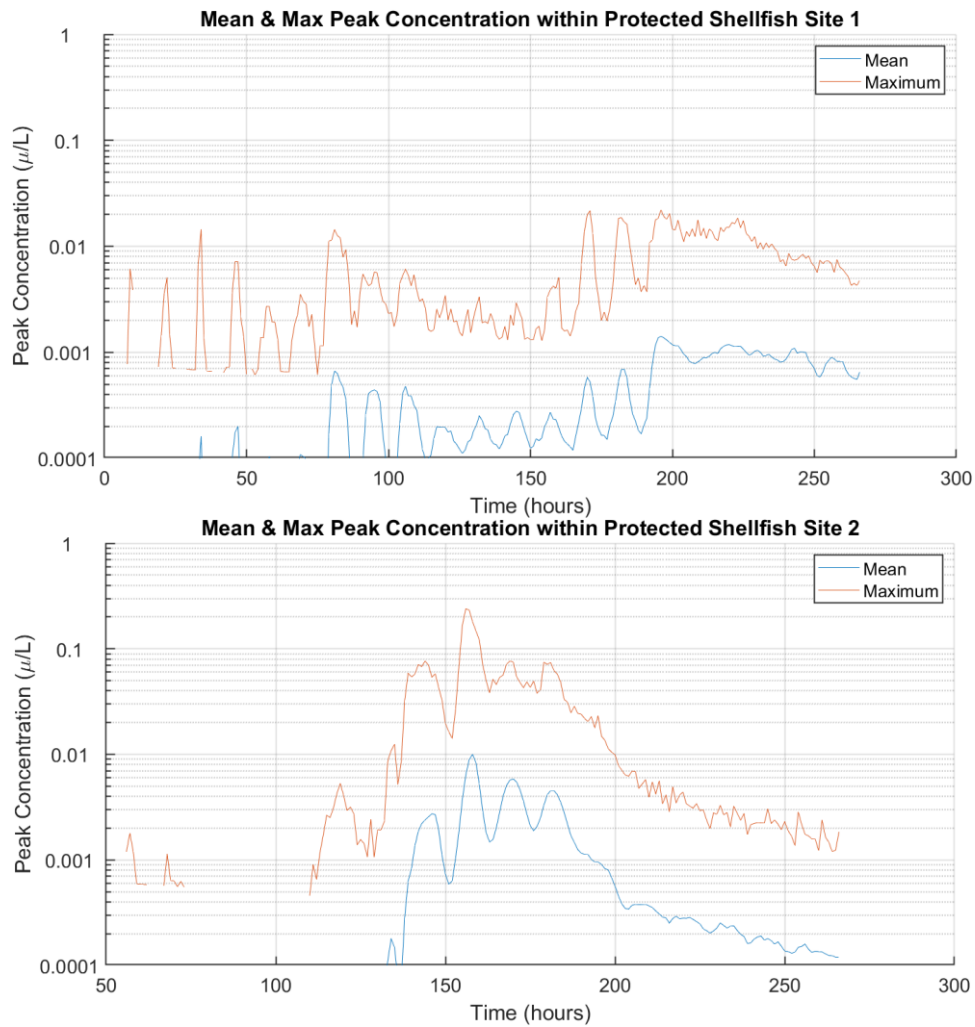


Figure 19. Mean and maximum peak concentrations over neap tides for special feature area 1 (top) and special feature area 2 (bottom)



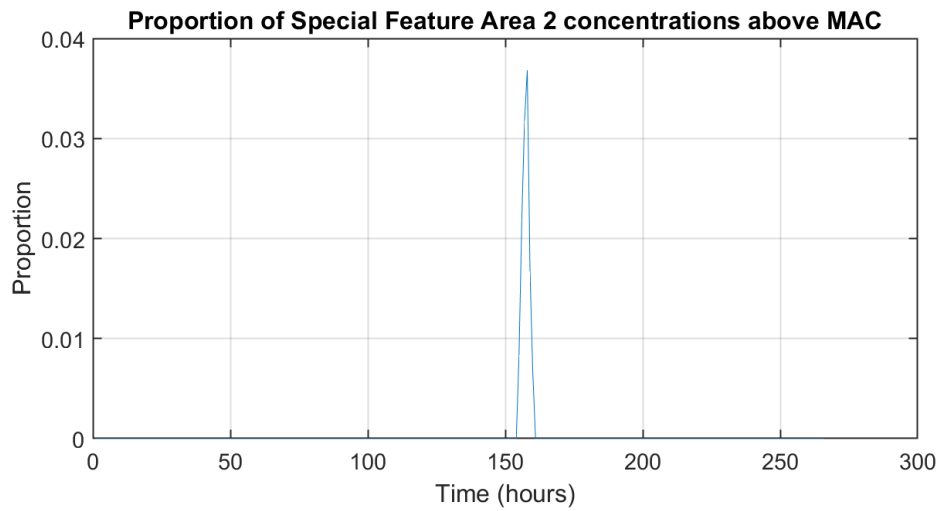


Figure 20. Proportion of Special Feature Area 2 concentrations above the 72-hour MAC during neap tides

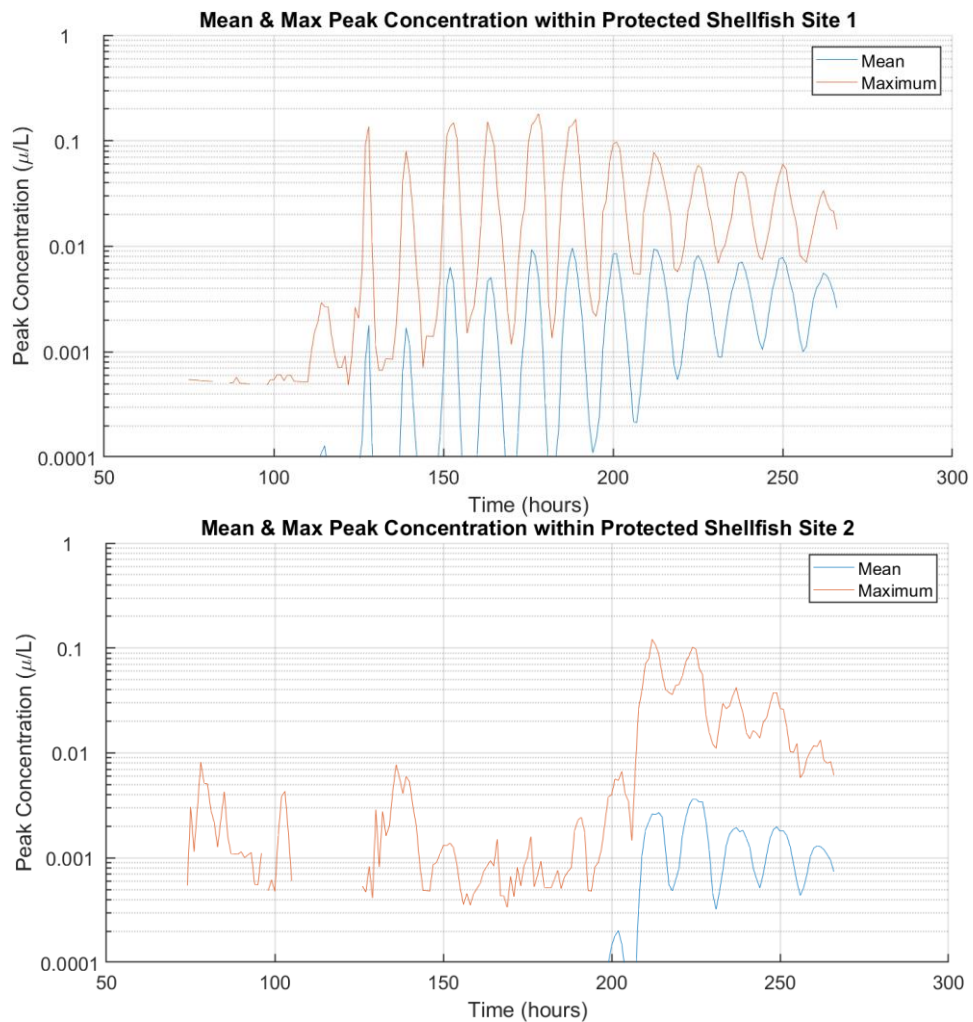


Figure 21. Mean and maximum peak concentrations over spring tides for special feature area 1 (top) and special feature area 2 (bottom)

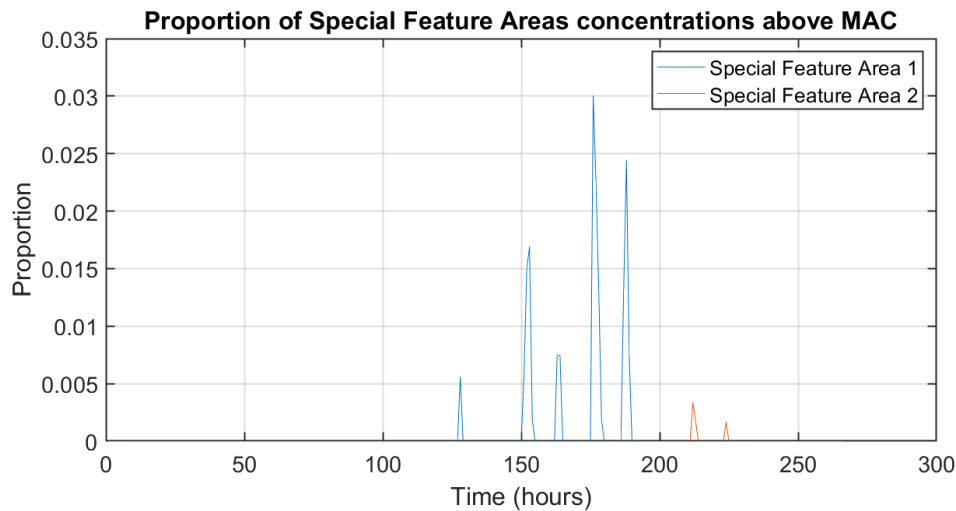


Figure 22. Proportion of Special Feature Areas concentrations above the 72-hour MAC during spring tides

#### 4 SUMMARY AND CONCLUSIONS

A total of 29 dispersion simulations have been performed to assess whether bath treatments at North Shore West salmon farm will comply with pertinent EQS. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 413 g of Azamethiphos for treatment, resulting in a total discharge over 7 days of 3.3 kg. Simulations were performed separately for modelled neap and spring tides, and the sensitivity of the results to key model parameters was tested. Results are summarised in Table 6.

Table 6. Summary of Results

<b>Site Details</b>	
Site Name:	North Shore West
Site Location:	Loch Erisort
Peak Biomass (T):	1,650
<b>Pen Details</b>	
Number of Pens:	8
Pen Circumference (m):	120
Working Depth (m):	9
Pen Group Configuration:	2 x 4
<b>Azamethiphos Consent</b>	
Recommended 3-hour (g):	413
Recommended 24-hour (g):	413

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 413 g, should consistently comply with the EQS. The peak concentration during the baseline simulation after 240 hours (72 hours after the final treatment) was less than  $0.1 \mu\text{g L}^{-1}$ , the maximum allowable concentration, and the area where concentrations exceeded the EQS of  $0.04 \mu\text{g L}^{-1}$  was substantially less than the allowable  $0.5 \text{ km}^2$ . In all simulations

performed, including sensitivity testing, the EQS and MAC criteria were met. Further simulations over a neap tide from later in 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. Peak concentrations of Azamethiphos near the seabed within the two identified special feature areas (SEPA, 2023) were found to be consistently low throughout the simulation and did not breach either MAC level for more than a couple of hours at any time. Therefore, it is believed that the requested daily quantity of 413 g of azamethiphos can be safely discharged at North Shore West without breaching the MAC or EQS.

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