# Azamethiphos Dispersion Modelling
# Hellisay, Isle of Barra, CAR/L/1095612

**Mowi Scotland Limited**

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Mowi Scotland

[redacted]

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## EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Hellisay salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment per day was simulated. Each pen required 750 g of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azure) for treatment, resulting in a daily release of 750 g and a total discharge over 5 days of 3.75 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 750 g of azamethiphos, should comfortably comply with the EQS. The peak concentration during the baseline simulation after 168 hours (72 hours after the final treatment) was less than 0.1 µg/L, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg/L was substantially less than the allowable 0.5 $km^2$. The baseline simulation presented here was designed to be relatively conservative.

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

*Table 1. Summary of Results*

| | |
|---|---|
| **Site Details** | |
| Site Name: | Hellisay |
| Site Location: | Isle of Barra |
| Peak Biomass (T): | 2,150 |
| **Pen Details** | |
| Number of Pens: | 5 |
| Pen Dimensions: | 200m circumference |
| Working Depth (m): | 10 |
| Pen Group Configuration: | 1 x 5 |
| **Azamethiphos** | |
| Recommended 3hr Consent (g): | 750 |
| Recommended 24hr Consent (g): | 750 |

# 1 INTRODUCTION

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

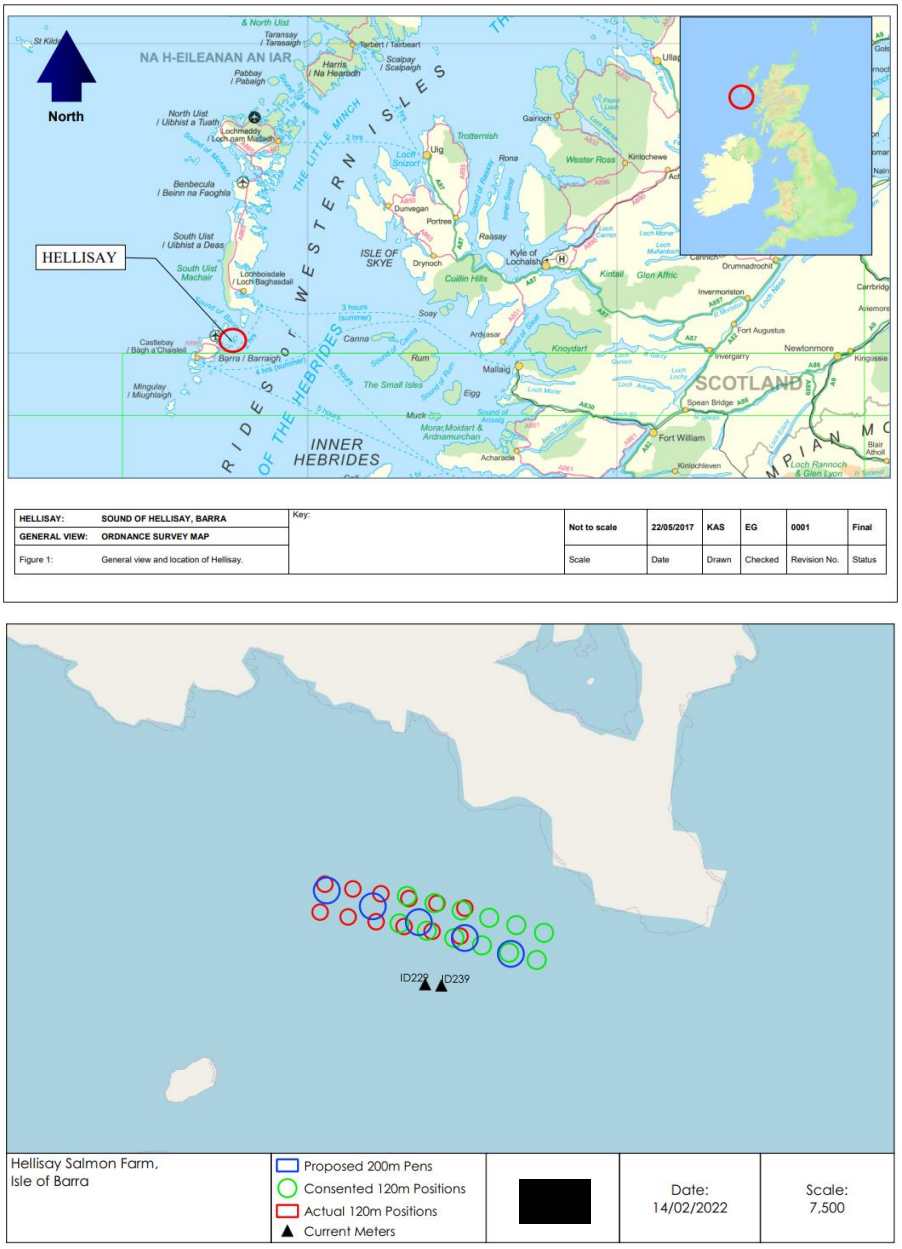


*Figure 1. Location of Hellisay salmon farm (top) and the location of the ADCP deployments (▲) relative to the proposed pen positions (**o**).*

## 1.1 Site Details

The site is situated off the south of the Isle of Hellisay, near the Isle of Barra (Figure 1). Details of the site are provided in Table 2. The receiving water is defined as open water.

*Table 2. Project Information*

| | | |
|---|---|---|
| **Site Details** | | |
| Site Name: | Hellisay | |
| Site Location: | Isle of Barra | |
| Peak Biomass (T): | 2,150 | |
| Proposed Feed Load (T/yr) | 5,493 | |
| Proposed Treatment Use: | Azamethiphos | |
| **Pen Details** | | |
| Group Location: | NF758031 | |
| Number of Pens: | 5 | |
| Pen Dimensions: | 200m circumference | |
| Grid Matrix (m): | 110 | |
| Working Depth (m): | 10 | |
| Cone depth (m): | 5 | |
| Pen Group Configuration: | 1 x 5 | |
| Pen Group Orientation (°G): | 105 | |
| Pen Group Distance to Shore (km): | 0.29 | |
| Water Depth at Site (m): | 23 | |
| **Hydrographic Data** | | |
| | **ID229** | **ID239** |
| Current Meter Position: | 75874, 803037 | 75914, 803034 |
| Depth at Deployment Position (m): | 22.48 | 24.13 |
| Surface Bin Centre Height Above Bed (m): | 17.73 | 17.72 |
| Middle Bin Centre Height Above Seabed (m): | 7.73 | 7.72 |
| Bottom Bin Centre Height Above Bed (m): | 3.73 | 3.72 |
| Duration of Record (days): | 66 | 59 |
| Start of Record: | 07/06/2018 | 13/08/2018 |
| End of Record: | 13/08/2018 | 12/10/2018 |
| Current Meter Averaging Interval (min): | 20 | 20 |
| Magnetic Correction to Grid North: | -4.13 | -4.09 |
| **Bath Treatments** | | |
| 3hr Recommended Consent Mass (g): | 750 | |
| 24hr Recommended Consent Mass (g): | 750 | |

# 2 MODEL DETAILS

## 2.1 Model Selection

The modelling approach adopted a coupled hydrodynamic and particle tracking method, whereby water currents in the region, modelled using a calibrated hydrodynamic model, advected particles representing the topical medicine around the model domain. Turbulent eddy diffusion was modelled using a random walk method. Outputs from the modelling were derived to assess the dispersion of the medicine following treatments against statutory Environmental Quality Standards. The modelling approach is described in full in the Hydrodynamic Model Description (Mowi Scotland Ltd, Hellisay Hydrodynamic Model Description, August 2022), and is only summarised here.

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

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

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

## 2.2 Model Domain and Boundary Conditions

The unstructured mesh used in the model was adapted from the East Coast of Lewis and Harris (ECLH) sub-model mesh of the Scottish Shelf Model (SSM; MS, 2016) (Figure 2). Model resolution was enhanced in the Barra & South Uist region particularly around the Mowi site at

Hellisay (Figure 3). The spatial resolution of the model varied from 25m in some inshore waters to 5km along the open boundary. The model consisted of 75,790 nodes and 143,144 triangular elements. Bathymetry was taken from the ECLH model, combined with data from a multibeam survey which took place at the site on 14th October 2009 (Figure 4). Given that topical medicine dispersion occurs in the upper water column, it was not deemed necessary to use highly detailed bathymetry data in the immediate vicinity to the cages.

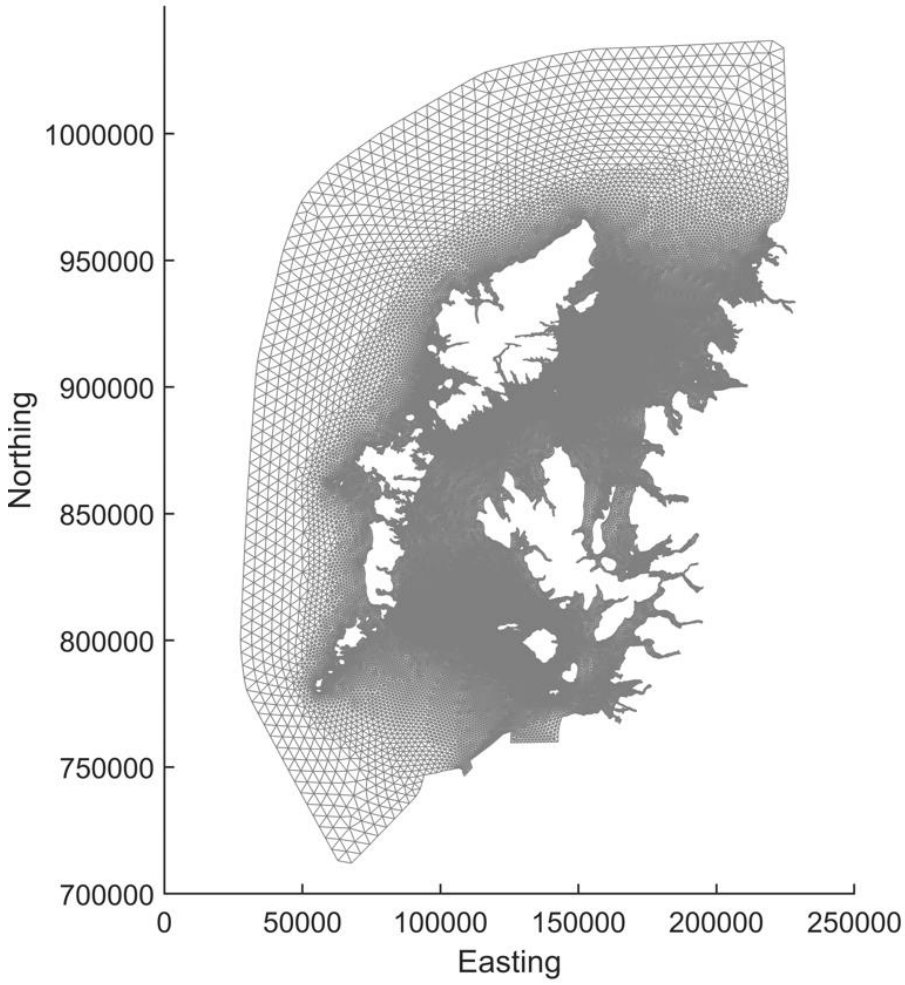


*Figure 2. The mesh and domain of the modelling study, adapted from the ECLH sub-model.*

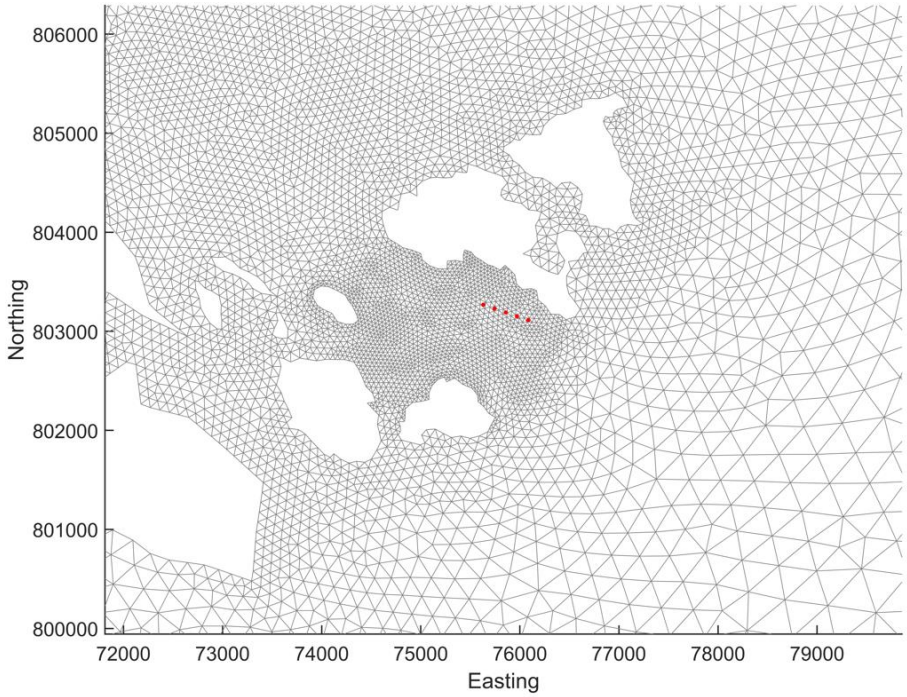


*Figure 3. The unstructured mesh around the Hellisay site in the modified model grid, with the proposed pen locations indicated (o).*

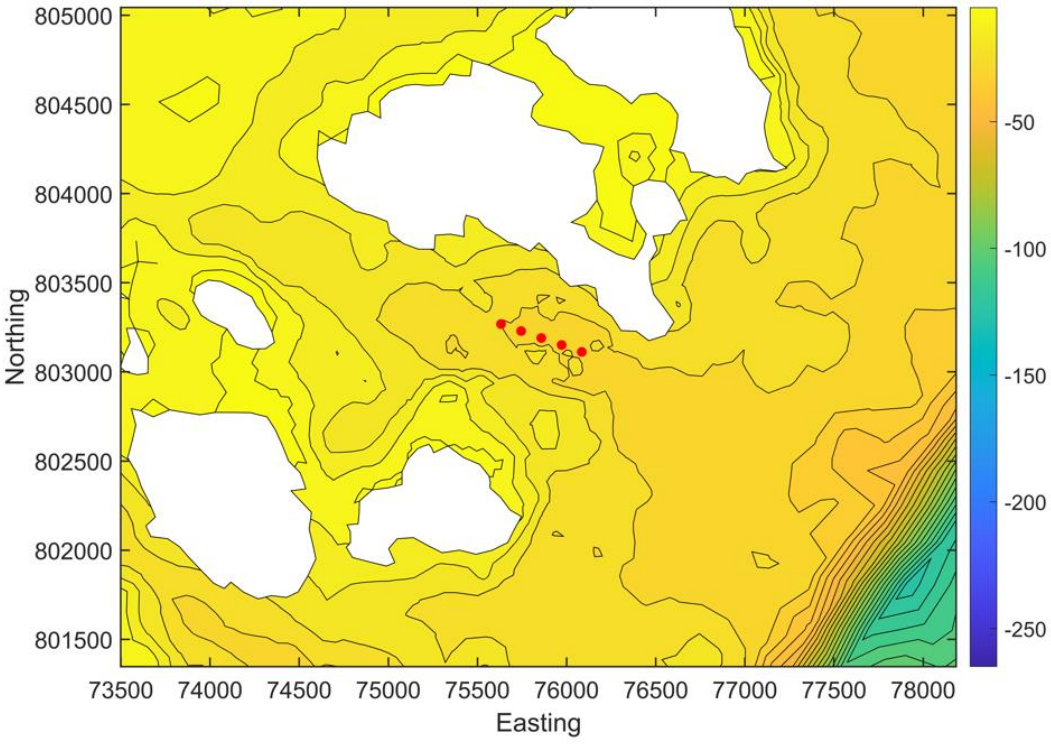


*Figure 4. Localised bathymetry (m) around Hellisay from the modified model.*

The model is forced at the outer boundaries by 8 tidal constituents ($M_2$, $S_2$, $N_2$, $K_2$, $O_1$, $K_1$, $P_1$ and $Q_1$) which were derived from tidal analysis (Pawlowicz et al., 2002) of the sea surface elevations at the closest nodes from the Scottish Shelf Model climatology (Marine Scotland, 2016). Spatially- and temporally-varying wind speed and direction data are taken from the ERA5 global reanalysis dataset (ECMWF, 2021) for the required simulation periods.

Full details of the calibration and validation of the hydrodynamic model are given in the Hydrodynamic Model Description (Mowi Scotland Ltd, Hydrodynamic Model Description, 2022).

## 2.3 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the UnPTRACK model (Gillibrand, 2021), simulates the dispersion of patches of medicine discharged from pens following treatment using tarpaulins. The UnPTRACK model uses the same unstructured mesh as the hydrodynamic model, and reads the flow fields directly from the hydrodynamic model output files. Therefore, no spatial or temporal interpolation of the current fields is required, although current velocities are interpolated to particle locations within UnPTRACK. The treatment scenario assumed 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 9 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 2.36 m was chosen as a realistic net depth during application of the medicine for 200m 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 3.75 kg of azamethiphos released during treatment of the whole farm (5 pens). Particles were released from random positions within a pen radius of the centre and within the 0 – 2.36 m depth range. The simulations used *ca. 375580* numerical particles in total, each particle representing 10 mg of azamethiphos.

Each simulation ran for a total of 217 hours (9.04 days). This covered the treatment period (96 hours), a dispersion period to the EQS assessment after 168 hours (72 hours after the final treatment), and an extra 49 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 50m x 50m squares using the same depth range as the treatment depth (i.e. 0 – 2.36 m). Using a regular grid for counting makes calculating particle concentrations and presenting the results easier.

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

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

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

Sensitivity analyses were conducted to assess the effects of:

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

The dispersion simulations were performed separately over neap and spring tides during 2018 (ID239) (Figure 5). A further set of simulations was performed over neap tides in 2018 (ID229) to confirm the adequacy of dispersion during the weakest tides (Figure 6).

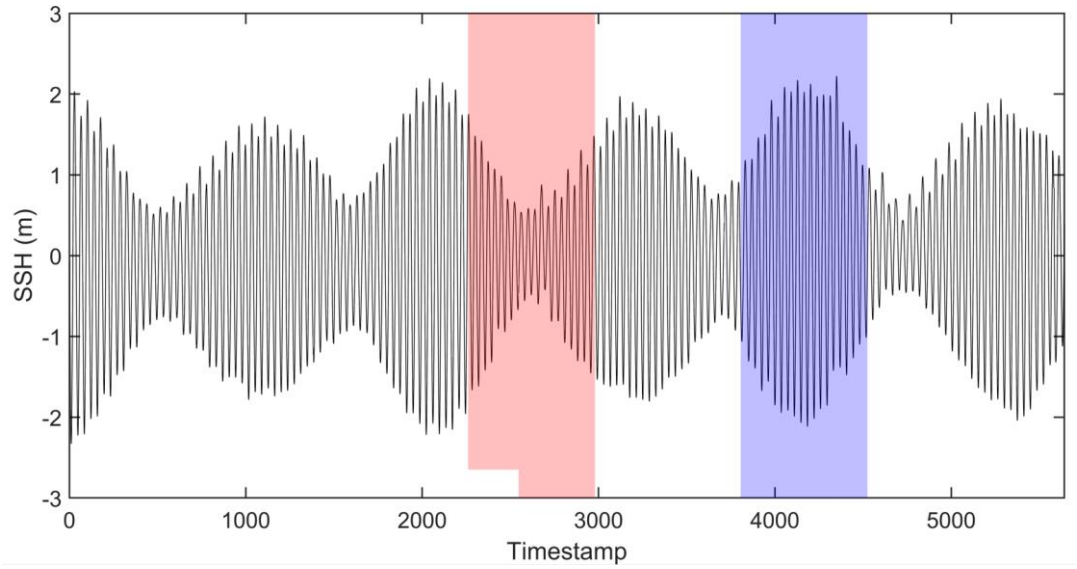


*Figure 5. Sea surface height (SSH) at Hellisay from 13th August –30th October 2018 (ID239). Dispersion simulations were performed over periods of neap tides (red, start day 15th September 2018) and spring tides (blue, start day 6th October 2018)*

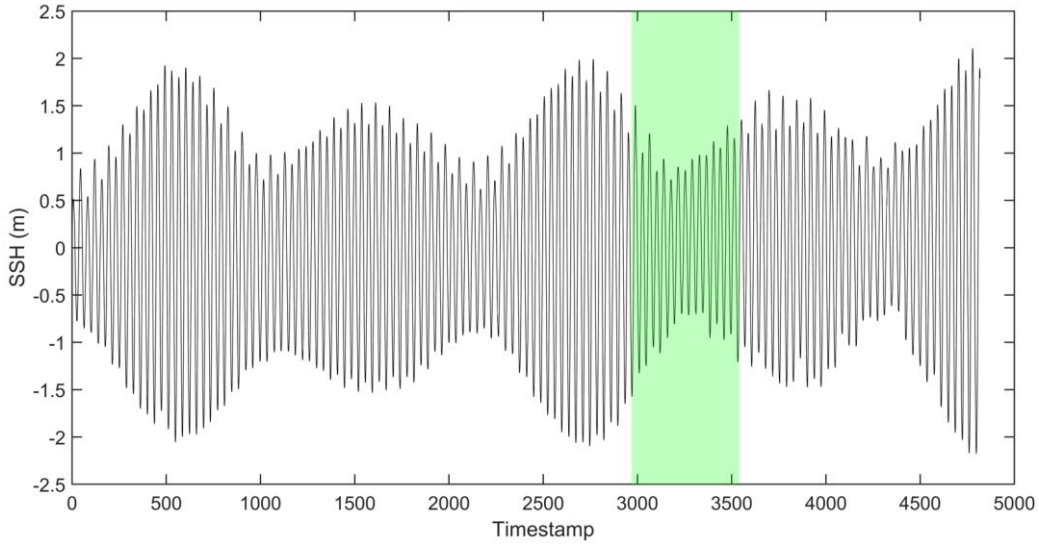


*Figure 6. Sea surface height (SSH) at Hellisay from 7th June 2018 – 13th August 2018 (ID229). Dispersion simulations were performed over periods of neap tides (green, start day 2nd July 2018).*

## 2.4 Medicine Dispersion Simulations

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

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

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

| Pen | Easting | Northing | Net Depth (m) | Treatment Mass (kg) | Release Time (hr) |
|---|---|---|---|---|---|
| 1 | 75632 | 803268 | 2.36 | 0.75 | 0 |
| 2 | 75745 | 803229 | 2.36 | 0.75 | 24 |
| 3 | 75858 | 803190 | 2.36 | 0.75 | 48 |
| 4 | 75972 | 803151 | 2.36 | 0.75 | 72 |
| 5 | 76085 | 803112 | 2.36 | 0.75 | 96 |

*Table 4. Dispersion model simulation details for the treatment simulations of 5 pens at Hellisay.*

| Set | Run No. | $T_{1/2}$ (h) | $K_H$ | $K_V$ | Start Time |
|---|---|---|---|---|---|
| Neap Tides, Start day = 34 (15th September 2018, ID239) | | | | | |
| 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 | 0.18 | 0.001 | 00:00 |
| | 11 | 134.4 | 0.05 | 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 = 55 (6th October 2018, ID239) | | | | | |
| 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 | 0.18 | 0.001 | 00:00 |
| | 18 | 134.4 | 0.05 | 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 = 42 (2nd July 2018, ID229) | | | | | |
| 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 | 0.18 | 0.001 | 00:00 |
| | 25 | 134.4 | 0.05 | 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 $L^{-1}$ 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 8.39 cm $s^{-1}$ was used from

ID239 (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*

| Parameter | Value |
|---|---|
| Mean current speed ($ms^{-1}$) | 0.0839 |
| Area of 160m pen ($km^2$) | 0.003183 |
| Distance from shore (km) | 0.450 |
| Mean water depth (m) | 24.83 |
| Treatment Depth (m) | 2.36 |
| **Mixing zone ellipse area ($km^2$)** | **0.1323008** |

For the 3-hour EQS assessment, the baseline runs for neap and spring tides (Runs 1 and 14 in Table 4) were repeated, but with results output every 20 minutes and the runs were truncated, lasting only until 3 hours after the final treatment. The area of the medicine patch for each individual treatment was then calculated over the 3-hour period following its release, and the area exceeding 250 ng $L^{-1}$ determined. Concentrations from these simulations were calculated on a 10m x 10m grid (rather than a 50m x 50m grid) in order to more accurately calculate the smaller areas of medicine over the initial 3-hour period.

## 2.6 Diffusion Coefficients

Selection of the horizontal diffusion parameter, $K_H$, was guided by dye releases conducted at the near-by Stulaigh site by Anderson Marine Surveys Ltd on 25th April 2017, along with several other dye release studies undertaken at other salmon farm locations. Dye tracking studies proceed by releasing a known quantity of dye into the sea, and then attempting to map the resulting dye patch as it disperses over time by deploying a submersible fluorometer from a boat. Each survey of the patch takes a finite amount of time (typically less than 30 minutes) and is usually made up of several transects which attempt to criss-cross the patch. An estimate of horizontal diffusivity can be made from each transect, but the location of the transect relative to the centre of the patch (and the highest concentrations) is often uncertain. The estimates of horizontal diffusivity shown in Figure 7 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 Stulaigh gave a mean horizontal diffusivity of 0.18 $m^2\ s^{-1}$. 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.

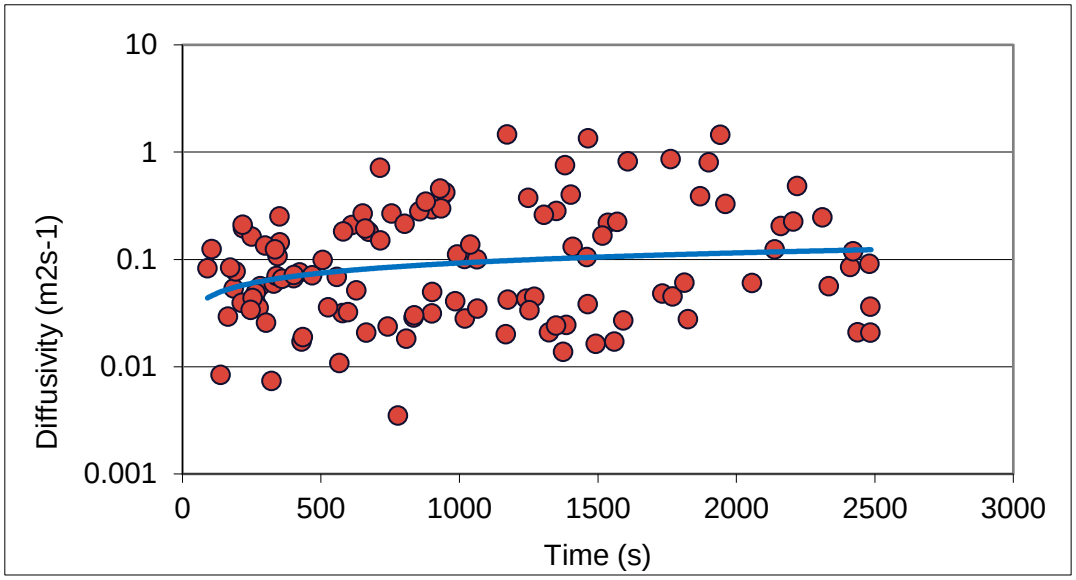


*Figure 7. Estimated horizontal diffusivity ($m^2$ $s^{-1}$) from dye release experiments at Stulaigh on 25th April 2017. The mean diffusivity was 0.18 $m^2$ $s^{-1}$.*

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

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

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

A number of dye releases have been conducted for Mowi Scotland Ltd in recent years to assess horizontal diffusivity at salmon farm sites. The maximum concentration measured in each post-release survey was identified (each comprised of a number of individual transects) and was then plotted against the nominal time for that survey (typically accurate to ±15 minutes). The results are shown in Figure 8. A nominal mixed depth of H = 5m was used (see also Dale et al., 2020).

The results support the notion that horizontal diffusivity in the Scottish marine environment is typically greater than 0.1 $m^2$ $s^{-1}$. The observed maximum concentrations, particularly after about 15 minutes (900s), fall faster than a diffusivity of 0.1 $m^2$ $s^{-1}$ would imply, indicating greater diffusion. There is considerable uncertainty in the data, because it is difficult during dye surveys to repeatedly measure the point of peak concentration. Nevertheless, we can say that no data thus far collected infer a horizontal diffusion coefficient of less than 0.1 $m^2$ $s^{-1}$. At periods longer than one hour (3600s), none of the data implied a horizontal diffusivity of less than 0.3 $m^2$ $s^{-1}$. We can conclude that using $K_H$ = 0.1 $m^2$ $s^{-1}$ is a conservative value for modelling bath treatments over periods greater than about half-an-hour.

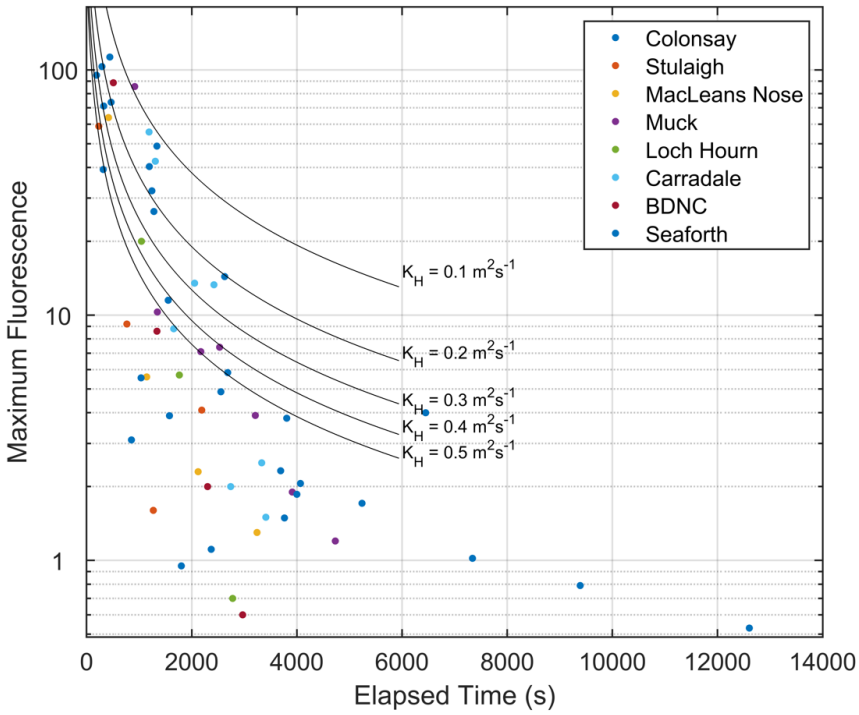


*Figure 8. Maximum fluorescence measured following dye releases at a number of Mowi sites in Scotland. The black lines indicate the rate at which the maximum concentration would fall at different horizontal diffusivities.*

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

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

# 3 RESULTS

## 3.1 Dispersion During Neap Tides, September 2018 (ID239)

A standard treatment of 5 x 200m pens, with a reduced net depth of 2.36 m and assuming 1 pen could be treated per day at a treatment concentration of 100 µg/L, resulted in a treatment mass per pen of azamethiphos of 750 g, a daily (24-h) release of the same mass of 750 g and a total treatment release of 3.75 kg over 96 hours. The dispersion of the medicine during and following treatment from Run001 (Table 4) is illustrated in Figure 9. After 24 hours, as the second treatment on day 2 was discharged, discrete patches of medicine are evident from the first treatment release from the first day. The maximum concentration at this time is about 100 µg/L, due to the release of the second treatment. After 72 hours, as the treatment is discharged, discrete patches of medicine from the previous treatment releases are still evident, but the patches of medicine have rapidly dispersed and are already down to concentrations of the same order as the EQS (0.04 µg/L). The maximum concentration at this time was again about 100 µg/L, due to the release of the fourth treatment.

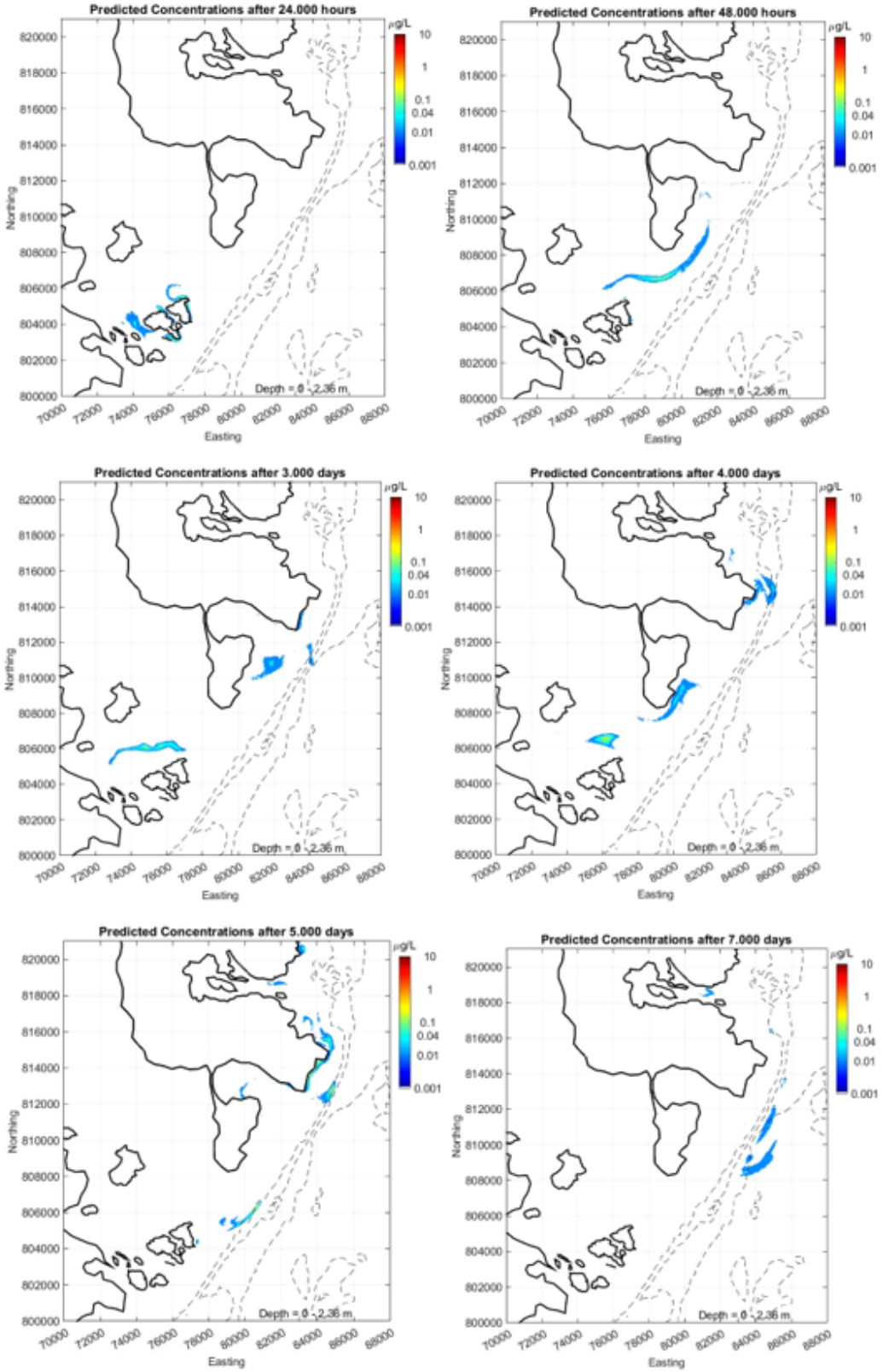


*Figure 9. Predicted concentration fields for a dispersion simulation at neap tides after 24 hours (top left), 48 hours (top right), 72 hours (middle left), 96 hours (middle right), 120 hours (bottom left) and 168 hours (bottom right).*

The treatment schedule completed after 96 hours (4 days). At this stage, the medicine released on earlier days had already dispersed north-east. 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 96 hours, the treatment patches were rapidly dispersed and concentrations rapidly fell away below the EQS. Remnants of medicine are seen in the Sea of the Hebrides but at concentrations below the MAC.

The time series of maximum concentration from this simulation is shown in Figure 10. The 5 peaks in concentration of ~100 µg/L following each treatment event over the first 5 days are evident. Following the final treatment after 96 hours, the maximum concentration fell steadily away (Figure 10). A default half-life of 134.4 h (5.6 days) was used. The maximum concentration seventy-two hours after the final treatment (time = 168 hours) was well below 0.1 µg/L, the maximum allowable concentration (MAC).

The area where the EQS of 0.04 µg/L was exceeded peaked at about 1.1 $km^2$ following the final treatment, but had fallen below 0.5 $km^2$ within 48h of the final treatment; by 72h after the final treatment, the exceeded area was close to zero (Figure 9 and 10).

These results indicate that, with a horizontal diffusion coefficient of 0.1 $m^2 s^{-1}$, and a medicine half-life of 134.4 h, the environmental quality standards are comfortably achieved. In the following sections, the sensitivity of the model results to the medicine half-life, diffusion coefficients and tidal state are examined.

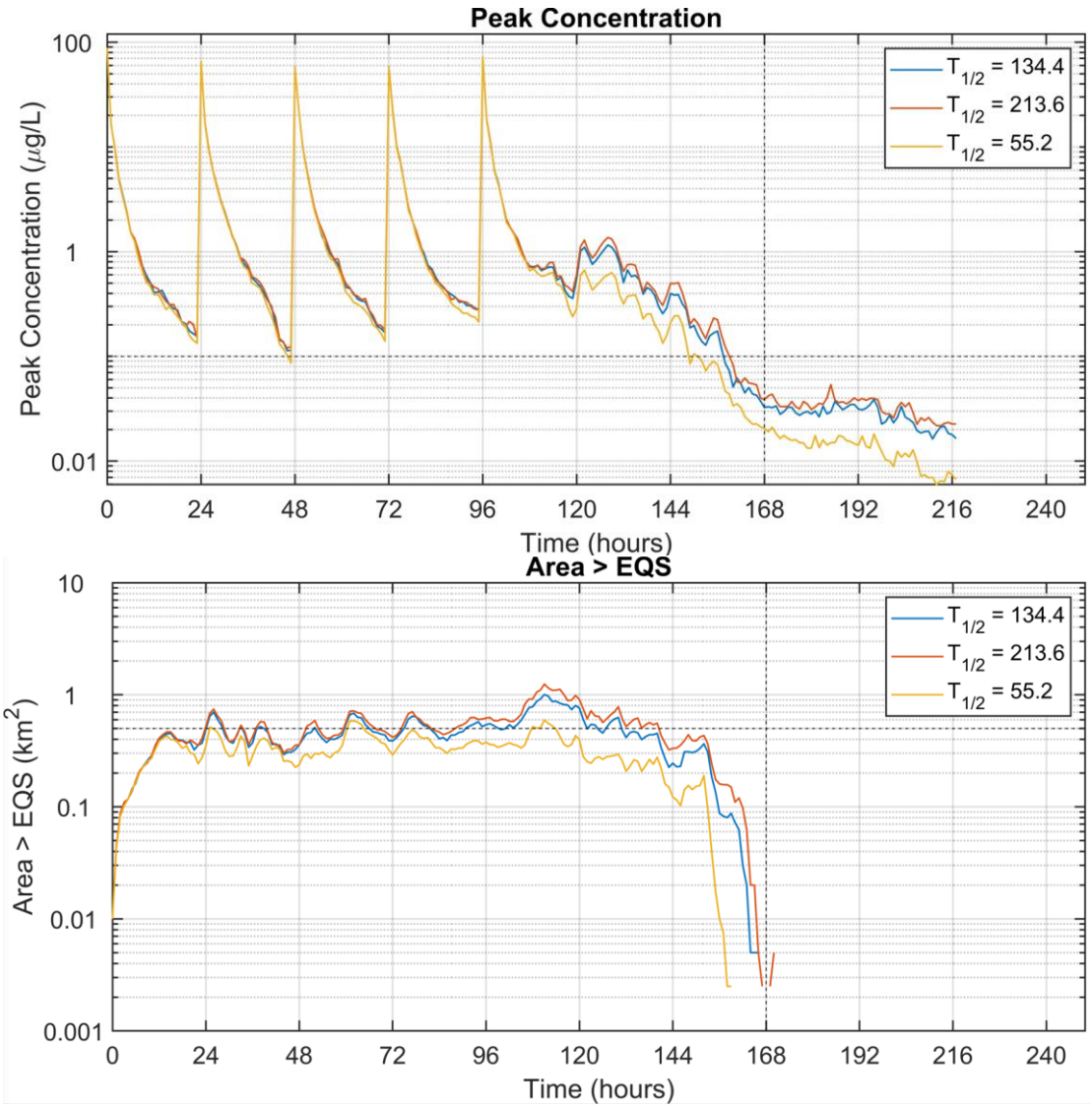


*Figure 10. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tide with varying medicine half-life ($T_{1/2}$). The MAC and area limit 72 hours after the final treatment (Time = 168 h) of 0.1 µg/L and 0.5 km$^2$ are indicated by the horizontal dashed lines.*

## 3.2 Sensitivity to Half-Life

The EQS was achieved, and was comfortably passed with all half-lives used (Figure 10). The area where the EQS of 0.04 µg/L is exceeded peaked at about 1.1 km$^2$ following the final treatment, but had fallen well below 0.5 km$^2$, for all simulated half-lives, within 72 hours of the final treatment (Figure 10). The area remained below 0.5 km$^2$ thereafter.

## 3.3 Sensitivity to Diffusion Coefficients

The model results were tested for sensitivity to the horizontal and vertical diffusion coefficients used. The horizontal diffusion coefficient used for the standard runs was $K_H$ = 0.1 $m^2$ $s^{-1}$. Simulations were also performed with lower and higher values of $K_H$, specifically $K_H$ = 0.18 $m^2$ $s^{-1}$ and $K_H$ = 0.05 $m^2$ $s^{-1}$ (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 168 hours (72 hours after the final treatment) with any of the different horizontal diffusion coefficients. The area limit of 0.5 $km^2$ was also comfortably met in all cases.

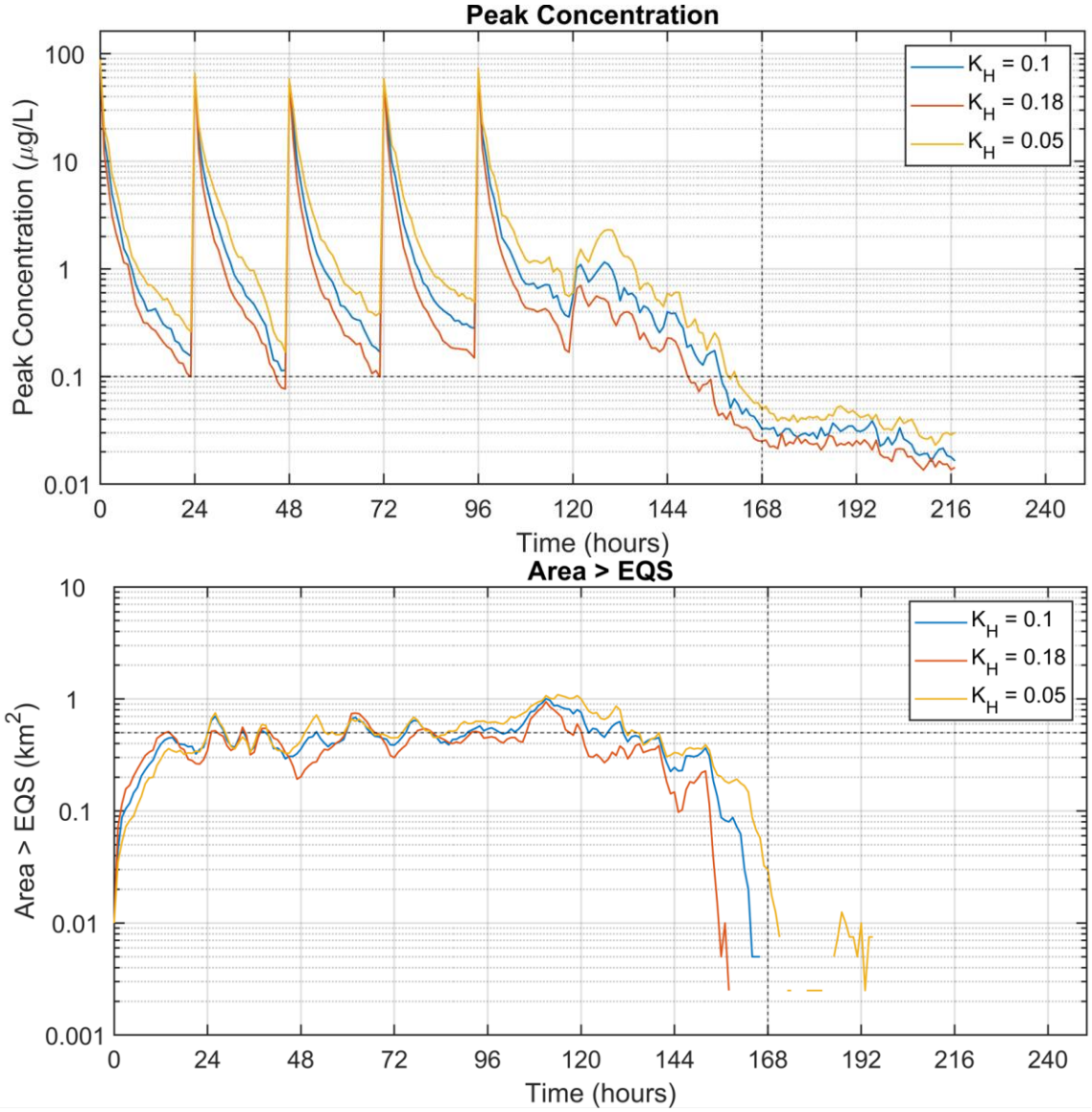


*Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient $K_H$ ($m^2$ $s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 168 h) of 0.1 µg/L and 0.5 $km^2$ are indicated by the horizontal dashed lines.*

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

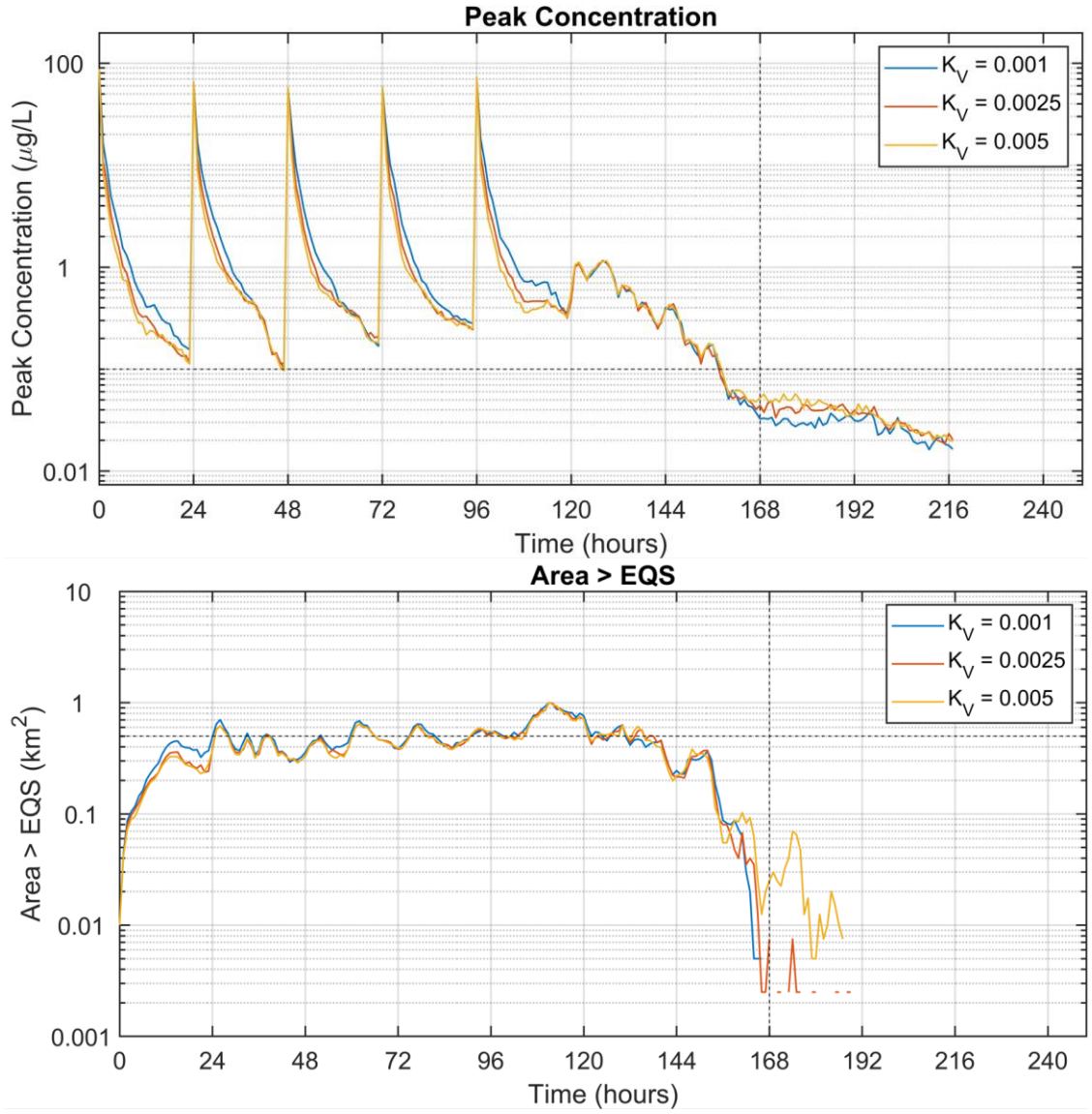


*Figure 12. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient $K_V$ ($m^2 s^{-1}$). The MAC and area limit 72 hours after the final treatment (Time = 168 h) of 0.1 µg/L and 0.5 $km^2$ are indicated by the horizontal dashed lines.*

## 3.4 Sensitivity to Release Time

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

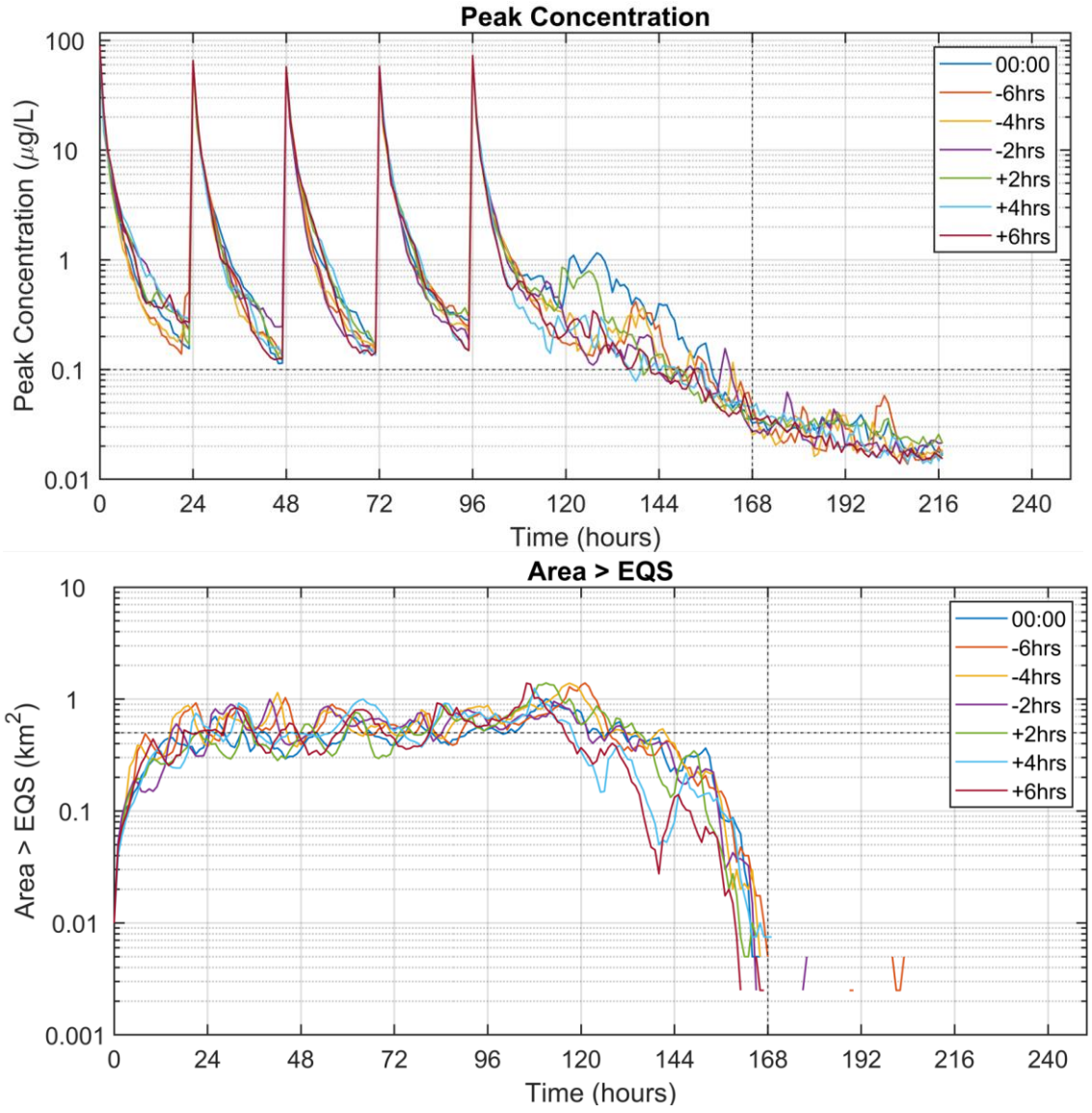


*Figure 13. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 168 h) of 0.1 µg/L and 0.5 km² are indicated by the horizontal dashed lines.*

## 3.5 Dispersion during Spring Tides, October 2018 (ID239)

Dispersion simulations were carried out during modelled spring tides in October 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 750 g of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were achieved (Figure 14).

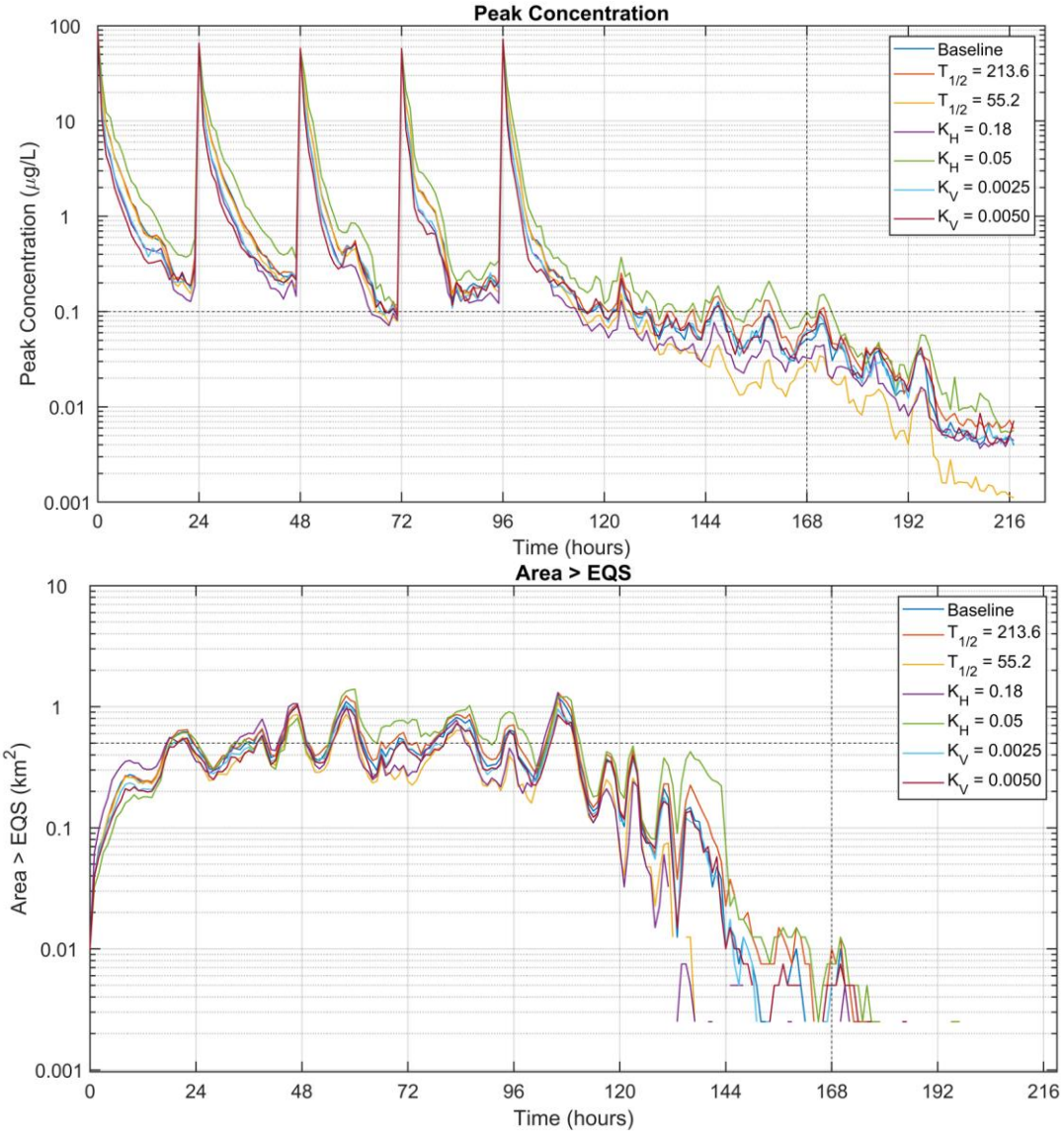


*Figure 14. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth, sixth and seventh set of model runs (Table 4). The model was run at spring tides with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient $K_H$ ($m^2 s^{-2}$) and vertical diffusion coefficient $K_V$ ($m^2 s^{-2}$). The MAC and area limit 72 hours after the final treatment (Time = 168 h) of 0.1 µg/L and 0.5 $km^2$ are indicated by the horizontal dashed lines.*

## 3.6 Dispersion During Neap Tides, July 2018 (ID229)

A further set of dispersion simulations during modelled neap tides in July 2018 were carried out (Figure 6), repeating the main set carried out for neap tides in September 2018 (Table 4). The same treatment scenario of 1 treatment per day was simulated, with each treatment using 750 g of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved. Some peaks in both concentration and area > EQS are observed and are assumed to be due to artefacts found in the model. But these quickly decrease back below the EQS in every case. The horizontal diffusion co-efficient used in these runs is also known to be highly conservative when looking at dispersion over time greater than an hour. These simulations demonstrate again that the modelled treatment regime will comfortably meet the EQS criteria.

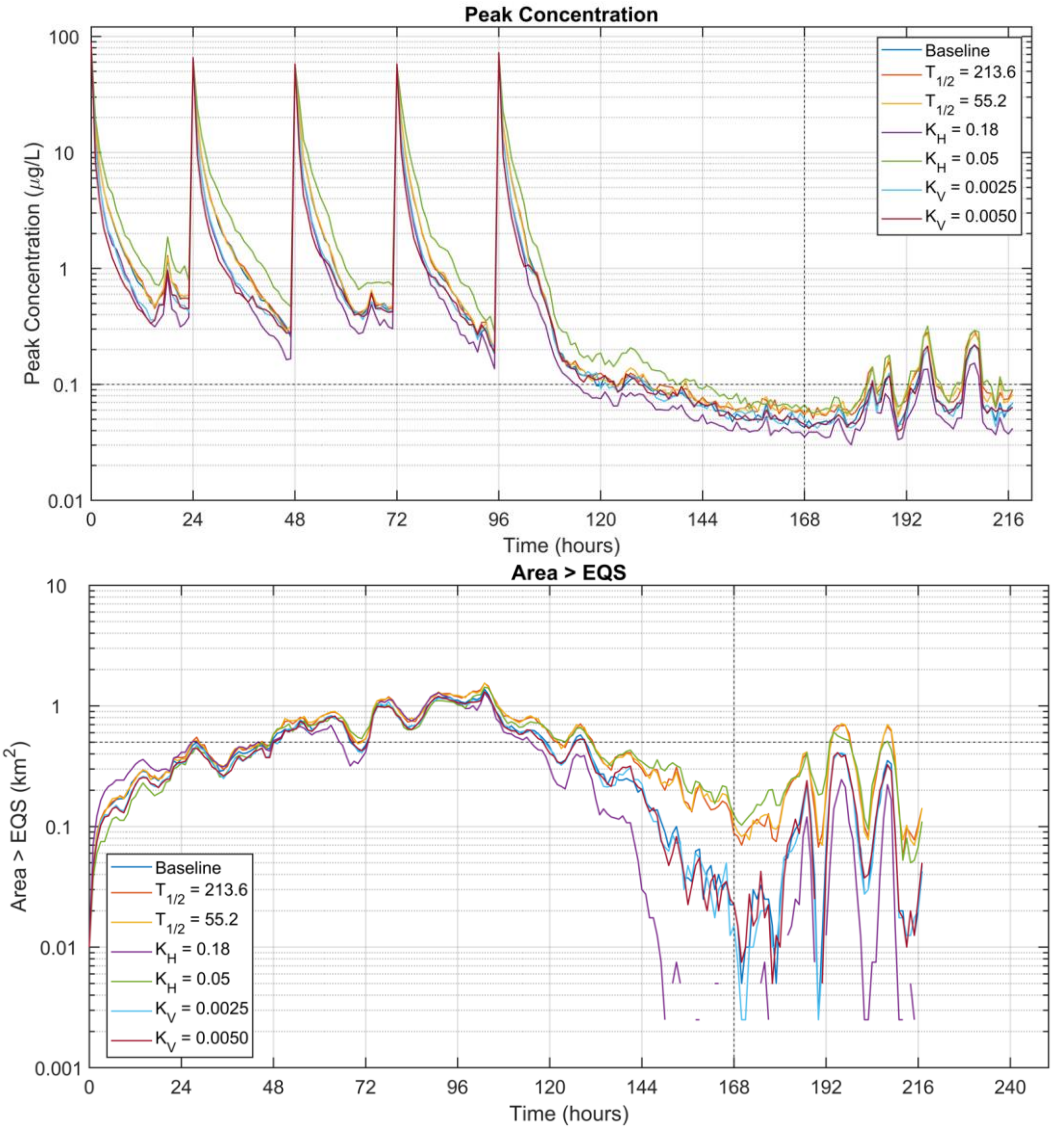


*Figure 15. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the eighth, nineth and tenth set of model runs (Table 4). The model was run at neap tides from July 2018 with varying medicine half-life $T_{1/2}$ (days), horizontal diffusion coefficient $K_H$ ($m^2 s^{-2}$) and vertical diffusion coefficient $K_V$ ($m^2 s^{-2}$). The MAC and area limit 72 hours after the final treatment (Time = 147 h) of 0.1 g/L and 0.5 $km^2$ are indicated by the horizontal dashed lines.*

## 3.7 3-Hour EQS

The 3-hour mixing zone is primarily a function of mean near-surface current speed at the site, and has traditionally been calculated by the BathAuto Excel spreadsheet. For calculation of the mixing zone, a mean surface current speed of 8.39 cm $s^{-1}$ was used from ID239 (Table 1) which was thought to be a representative value for the surface 0-2.36m layer at Hellisay. 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 15th September 2018) are shown in Figure 16. For each treatment, the area exceeding the EQS was comfortably less than the allowable mixing zone (0.132 $km^2$) after 3 hours. The peak concentration of 100 µg $L^{-1}$ decreased to less than 10 µg $L^{-1}$ within the 3-hour period.

For spring tide releases (first release on 6th October 2018), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 17). As for the neap tide simulation, the peak concentrations fell by an order of magnitude within the three hours.

This demonstrates that the discharge quantity of 750 g of azamethiphos from each of the five proposed 200m pens at Hellisay should not breach the 3-hour Environmental Quality Standard.

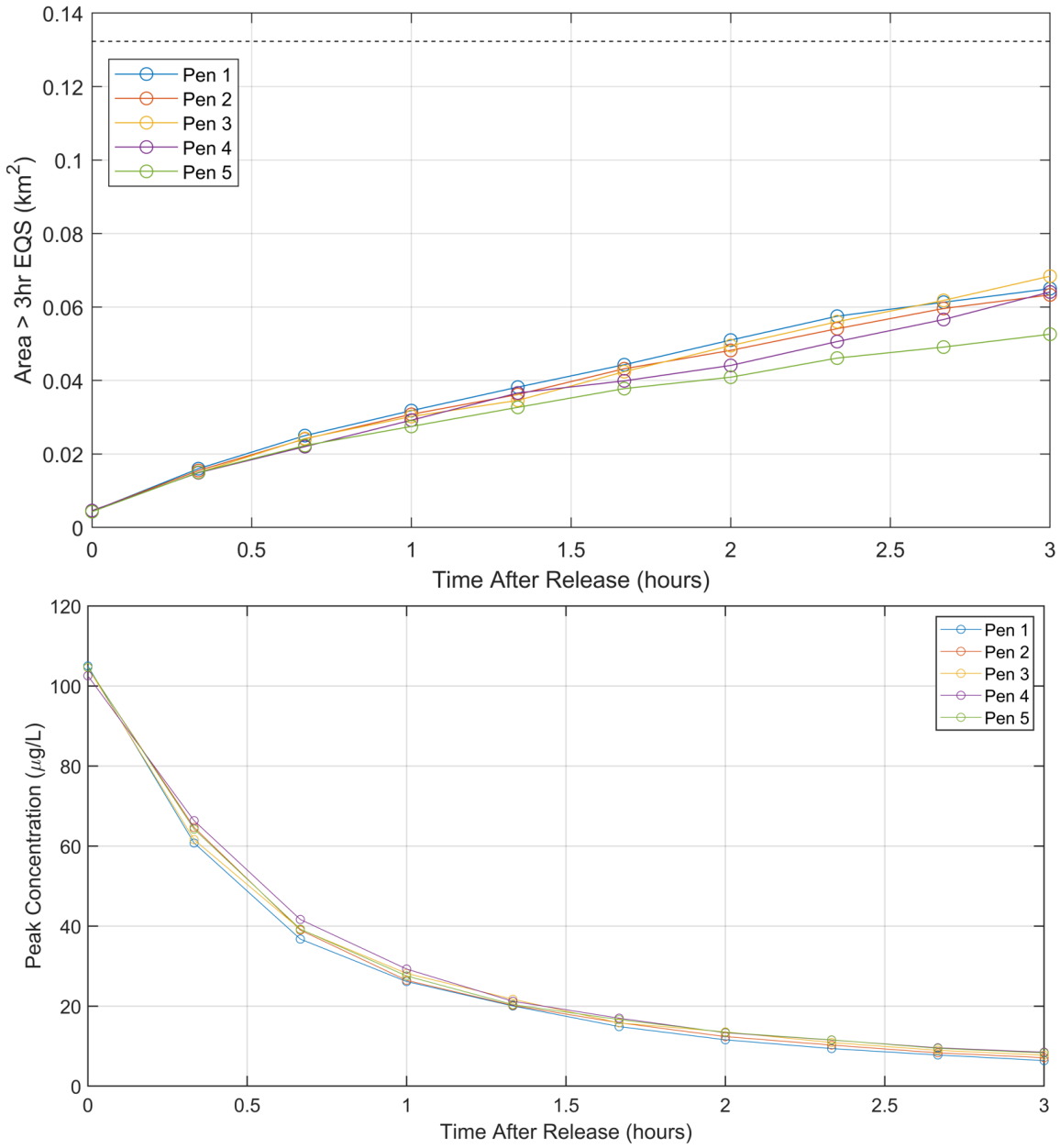


*Figure 16. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).*

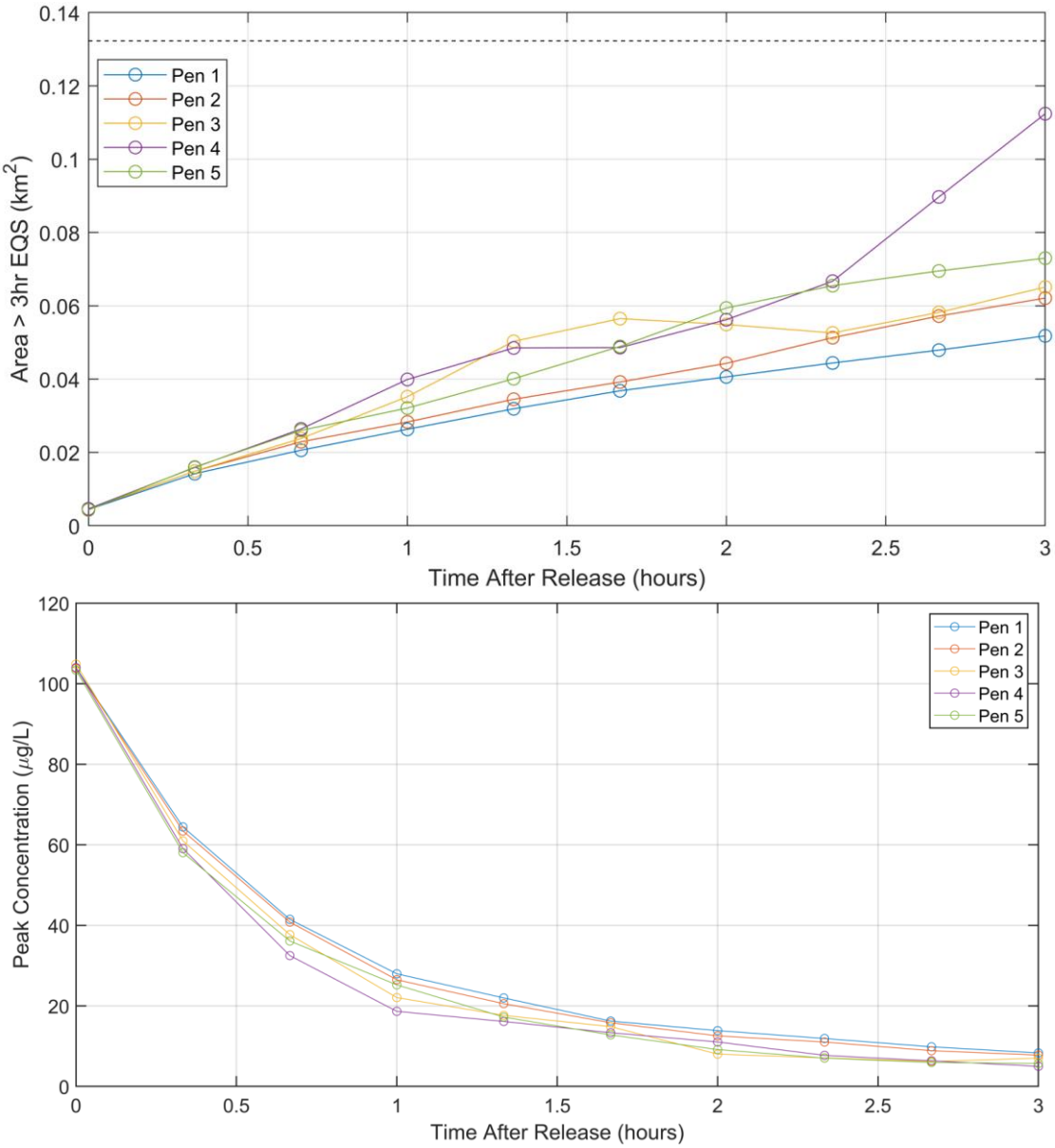


*Figure 17. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area indicated (---).*

## 4 SUMMARY AND CONCLUSIONS

A total of 29 dispersion simulations have been performed to assess whether bath treatments at Hellisay salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day was simulated. Each pen required 750 g of azamethiphos for treatment, resulting in a total discharge over 5 days of 3.75 kg. Simulations were performed separately for modelled neap and spring tides, and the sensitivity of the results to key model parameters was tested. Results are summarised in Table 6.

*Table 6. Summary of Results*

| | |
|---|---|
| **Site Details** | |
| Site Name: | Hellisay |
| Site Location: | Isle of Barra |
| Peak Biomass (T): | 2,150 |
| **Pen Details** | |
| Number of Pens: | 5 |
| Pen Dimensions: | 200m circumference |
| Working Depth (m): | 10 |
| Pen Group Configuration: | 1 x 5 |
| **Azamethiphos** | |
| Recommended 3hr Consent (g): | 750 |
| Recommended 24hr Consent (g): | 750 |

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 750 g, should consistently comply with the EQS. The peak concentration during the baseline simulation after 168 hours (72 hours after the final treatment) was less than 0.1 µg/L, the maximum allowable concentration, and the area where concentrations exceeded the EQS of 0.04 µg/L was substantially less than the allowable 0.5 $km^2$. In all simulations performed, including sensitivity testing, the EQS and MAC criteria were met. Further simulations over a neap tide from 2018 demonstrated that the modelled treatment regime consistently complied with the relevant EQS and MAC. For the simulation during spring tides, greater dispersion meant that the MAC and EQS were met very comfortably. Therefore, it is believed that the requested daily quantity of 750 g of azamethiphos can be safely discharged at Hellisay without breaching the MAC or EQS.

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

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