# Bath Treatment Dispersion Modelling at Reintraid

Dispersion modelling for Azamethiphos bath treatment consent limits for Reintraid farm site at Loch a' Chairn Bháin, Scotland.

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# 1 Introduction

BMT has been commissioned by Loch Duart Ltd (hereafter referred to as Loch Duart) to conduct an assessment of the fate and transport of the bath treatment agent Azamethiphos at the Reintraid finfish pen site located in Loch a’ Chairn Bháin, Sutherland, Scotland.

The purpose of this assessment is to support Loch Duart's proposal for an increase in biomass to 1,834 T at the site. The proposed increase will involve a change in cage layout from the existing fourteen 24 m x 24 m square pens to sixteen 80 m circumference circular pens, arranged in a 50 m x 50 m grid, with a 2 x 8 configuration. This will result in an increase in biomass from the currently consented 1,300 tonnes to 1,834 tonnes (SEPA 2021). Additionally, the proposal includes the consolidation of the two aquaculture sites, namely Reintraid (REI2) and Torgawn (TOR1) (currently inactive). By consolidating these sites, Loch Duart aims to achieve the targeted increase in biomass and optimise the overall operations.

This report presents the results of a hydrodynamic modelling study to simulate the dispersion of the Azamethiphos bath treatment under spring and neap tide scenarios. The assessment of Azamethiphos dispersion and comparison against Environmental Quality Standards is based on SEPA requirements for bath treatment modelling (SEPA 2019) as set out in the previously approved method statement (BMT 2023).

# 2 Hydrodynamic Modelling

## 2.1 Model

BMT has developed a numerical hydrodynamic and tracer model to simulate the fate and transport of Azamethiphos bath treatment at the Reintraid farm in Sutherland, Scotland (Figure 2.1) using a 3D hydrodynamic model TUFLOW FV.

## 2.2 TUFLOW FV Hydrodynamic Model

TUFLOW FV (https://www.tuflow.com) is a 3D flexible-mesh (finite volume) hydrodynamic model developed and distributed by BMT. It can be used for modelling a diverse array of inland and coastal water bodies and it is able to call the water quality model (WQM) library directly via a custom interface. The model accounts for variations in water level, the horizontal salinity distribution and vertical density stratification in response to inflows and surface thermodynamics. The finite volume numerical scheme solves the conservative integral form of the Non-Linear Shallow Water Equations in addition to the advection and transport of scalar constituents such as salinity, temperature, inert tracers and the state variables from the coupled biogeochemical model. The equations are solved in 3D with baroclinic coupling with both salinity and temperature using the UNESCO equation of state. Surface momentum exchange and heat dynamics are solved internally within the model from available meteorological boundary condition data.

## 2.3 Model mesh

This model has been developed as a nested TUFLOW FV model, within a larger model of the Scottish Shelf region, developed as part of the Seafood Innovation Fund (SIF) Project (BMT 2021). The two models include a low-resolution region scale model used to develop the general ocean circulation conditions; water levels, currents, temperature and salinity and a high resolution model encompassing the area of interest. The high-resolution model domain covers an overall area of 930,000 hectares, with two open boundaries of approximately 28 km extending along the southern section (The Little Minch) and 127 km extending along the northern section (North Minch) (Figure 2.1).

The model mesh has been refined as required for this study with reduced resolution offshore and increased resolution around pen sites. As per SEPA recommendations, a horizontal resolution of no greater than 25-30 m was maintained in areas around pen sites (Figure 2.1).

## 2.4 Model bathymetry

The digital elevation model (DEM) used to set model bathymetry comprised multiple sources to ensure suitable resolution for current speeds around the area of interest (Figure 2.1). The final bathymetry comprised the following:

- Bathymetry survey data provided by Loch Duart for the farm area.
- Transect data provided by Anderson Marine Surveys (Stuart Anderson pers com. 2023 Jan).
- Navionics.
- The DEM developed as part of the ongoing work in the SIF project (BMT 2021). The SIF project DEM includes regional bathymetry data from General Bathymetric Chart of the Oceans (GEBCO) and other sources provided as part of the SIF project data collection (BMT 2021).

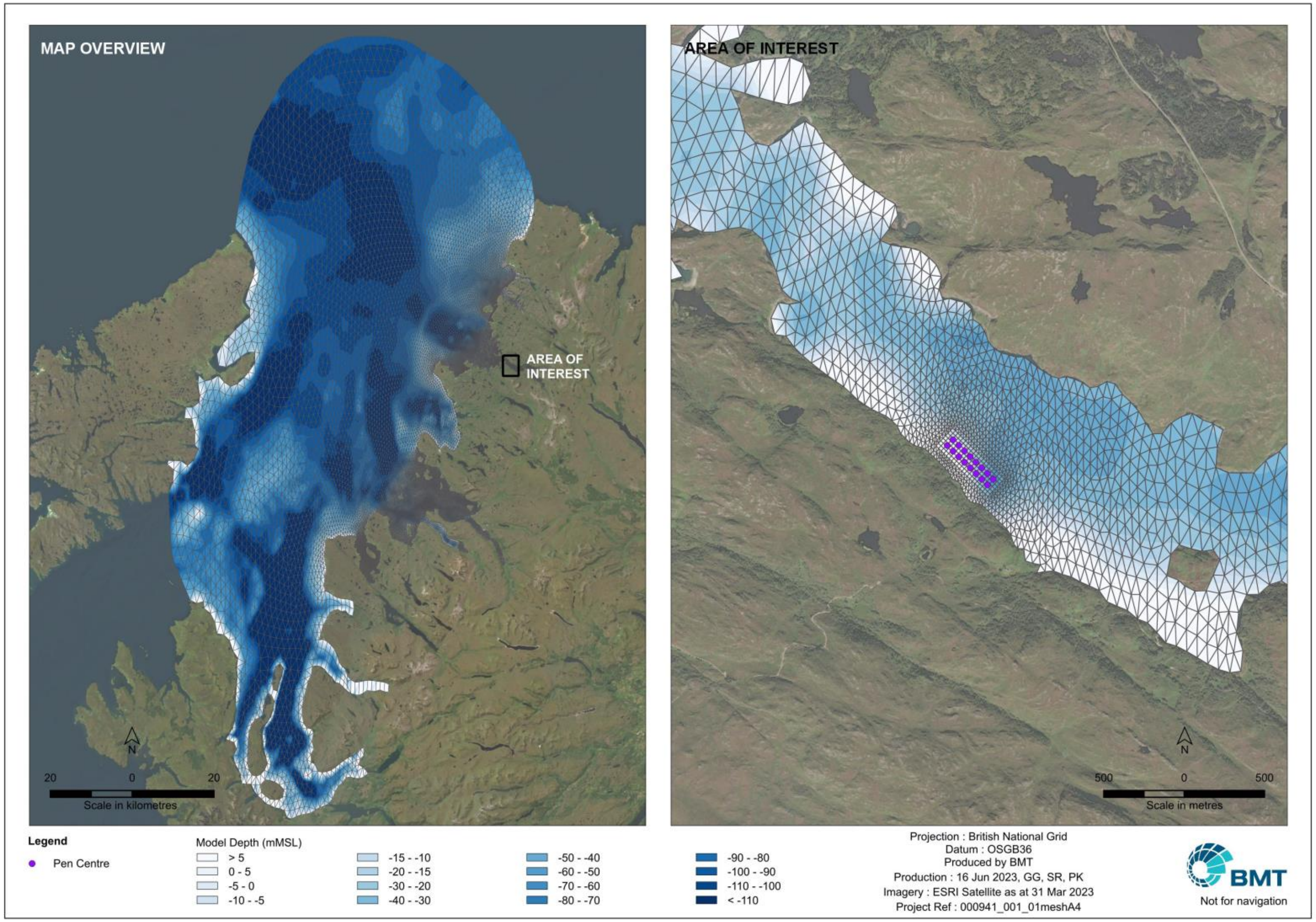


Figure 2.1 The mesh and bathymetry used for the high-resolution model.

## 2.5 Boundary conditions

The following meteorological and open tidal boundary conditions have been used for the larger regional model:

- The developed model extent included an open boundary that required temporal definition of water surface elevations. Due to the large extent of the model domain, tidal elevations varied spatially and temporally along the length of the offshore boundary. Tidal boundary conditions provided by the TPXO71 global tide model (Egbert & Erofeeva 2002) were used for the simulation.
- The model was provided with regional current forcing (residual water level, current magnitude and direction), temperature and salinity profiles at the open boundary. These were derived from the ocean general circulation model, HYCOM (http://hycom.org/) and varied both in space (longitude, latitude and elevation) and time. To capture the sub-daily regional processes, three-hourly HYCOM model datasets were prescribed at the ocean boundary.
- Atmospheric heat fluxes and water column heat dynamics were simulated internally within TUFLOW FV. Boundary condition data including wind, air temperature, long- and short-wave radiation, precipitation and relative humidity were derived from Meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 climate model (https://www.ecmwf.int/).
- The General Ocean Turbulence Model (GOTM) was coupled with the 3D TUFLOW FV hydrodynamic model in order to simulate the vertical mixing processes in the presence of density stratification (http://www.gotm.net/).

For the high-resolution nested model, the following boundary conditions were included:

- Open boundary conditions from the larger regional model as curtain profiles.
- Meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 climate model.

Note that, freshwater inputs to the area of interest were considered negligible and not included in either model.

## 2.6 Hydrodynamic Model Calibration

The hydrodynamic model was calibrated against data from an Acoustic Doppler Current Profiler (ADCP) located close to the farm site (Figure 3.1). The calibration process involved the comparison of water levels, velocity direction, velocity magnitude and the x and y component of the flow to observed data, adjusting model parameters and bathymetry to achieve a desired level of model fit.

ADCP data were provided by Loch Duart, over three consecutive monthly deployments to obtain 90 days of monitoring (TransTech Limited 2023a). The calibration period from 12/08/2022 to 10/11/2022 covered the deployment period.

The calibration has been done at 3 different depths throughout the water column:

- Sub-surface – approx. 5 m below the MSL (50 - 52 m above the seabed), and
- Mid water column – approx. 5 m below the pens (43 - 45 m above the seabed), and
- Bottom – 3 - 5 m above the seabed.

The pressure sensor's data showed that the ADCP remained undisturbed. There were some short-term changes in pitch, roll and heading during the 90-day deployment period but these were minor and well within the ADCP's tolerances for data auto-correction. Further details on the ADCP deployments, GPS calibration and data processing can be found in the hydrographic survey report for the Reintraid site (TransTech Limited 2023a).

Comparisons of model against observed data are shown in Figure 2.2 to Figure 2.4, noting that water level is the same in all three plots for reference. On the plots, statistics for R, BIAS (model bias), MAE (mean absolute error), and PD (percentage difference) are included for comparison.

### 2.6.1 Water level

- The R value is high (i.e. ≥0.95), signifying a strong correlation between the model predicted water level and the observed data.
- The tidal range predicted by the model is consistent with the observed data and predicts the variations in tidal range between spring and neap tides.
- The timing of the high and low water matches well between the ADCP and modelled data.
- This model has a water level calibration suitable for the use of modelling the dispersion of bath treatment.

### 2.6.2 Velocity magnitude

- There was a negative bias of 0.02 m/s for water velocities in the middle water column. At the seabed, the bias was 0 m/s, and at the surface (where bath treatment is released), it was 0.01 m/s (negligible). Indicating the model slightly underestimates middle water column velocities.
- Underprediction of the current speeds in the area of interest is consistent with a conservative approach leading to reduced rate of dispersion and dilution impact.
- The MAE is small for all three depths (0.02 - 0.04) and within the regulatory calibration guideline of 0.1 m/s (SEPA 2019).
- A possible cause of some difference is due to the ADCP having a standard deviation slightly over 0.5 cm/s at all depths.
- In the sub-surface layer, where most of the bath treatment is released, the model exhibits a slight underprediction of currents during the initial half of the calibration period. In contrast, during the latter half of the calibration period, the model slightly overpredicts current speeds. The overall comparison of timeseries data for the calibration period indicates a reasonably strong alignment between observed and modelled data.

### 2.6.3 Current direction

- For the sub-surface and near bed comparisons, the model was able to reproduce the stronger directional trends with low (< 3 %) percentage error.
- Given the low current speeds in the mid water level (where simulated current directions were not as well captured by the model), the overall simulated current directions were deemed suitable for use in the bath treatment dispersion model.

### 2.6.4 Flow velocity components

- Comparison of observed and predicted x and y components of the flow demonstrate that the model successfully represents changes in direction and speed.
- The BIAS and MAE were relatively low, highlighting a good comparison between the ADCP and modelled data.

Overall, the results of the calibration signified that the model was suitable for use in simulating bath treatment dispersion at the Reintraid site.

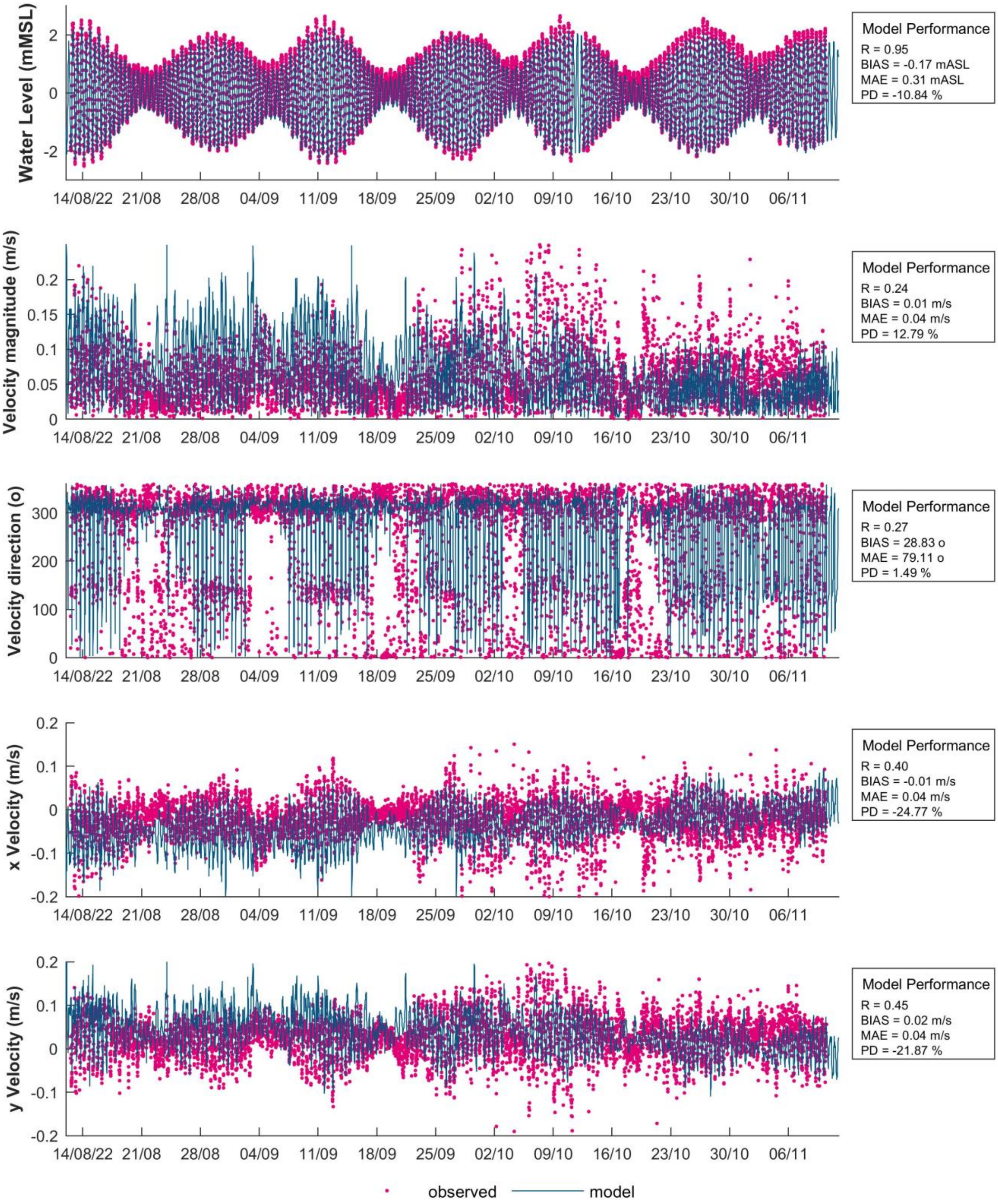


Figure 2.2 Model comparison to ADCP data at the sub-surface – approx. 5 m below the MSL (50 - 52 m above the seabed).

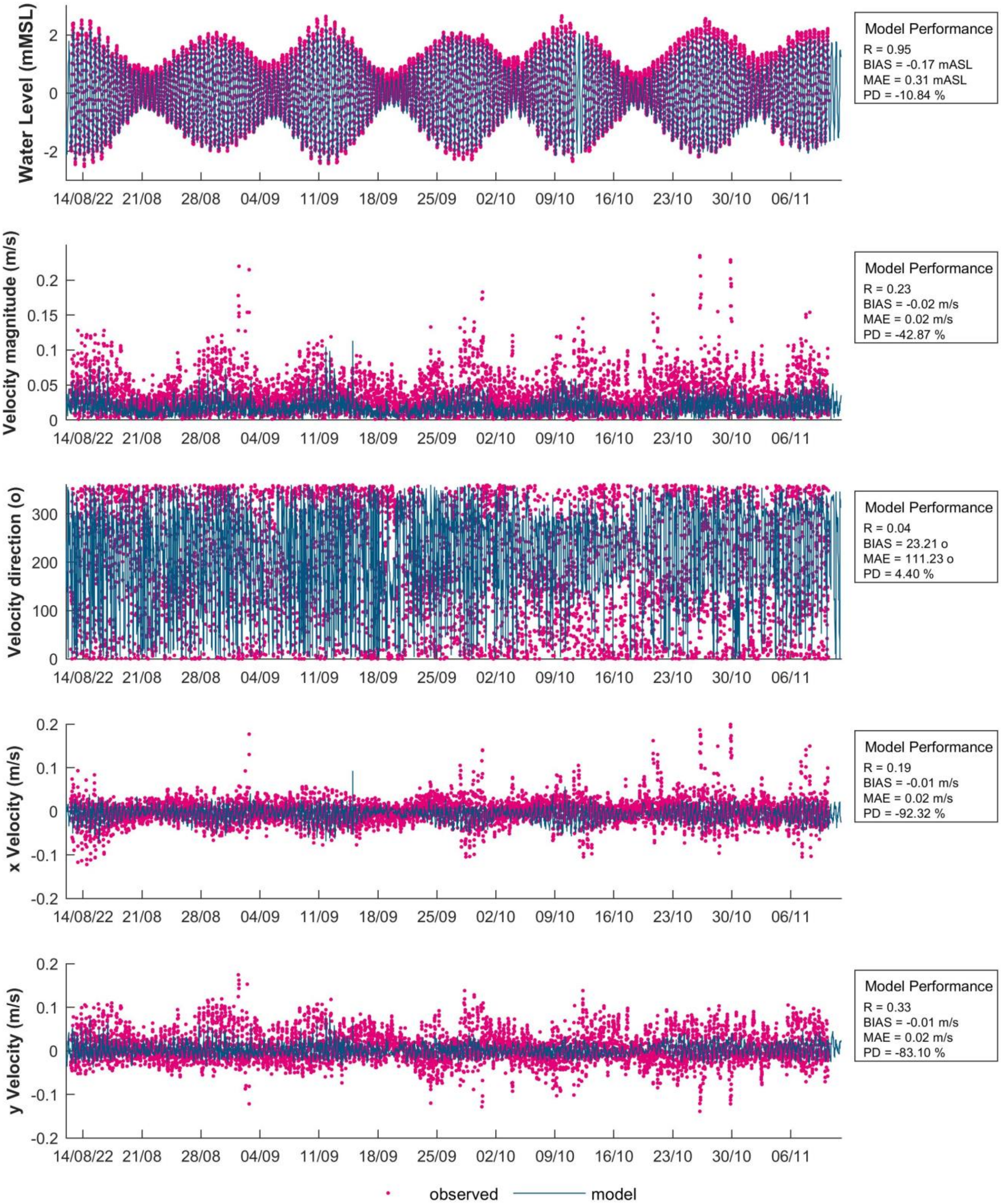


Figure 2.3 Model comparison to ADCP data at the mid water column - approx. 5 m below the pens (43 - 45 m above the seabed).

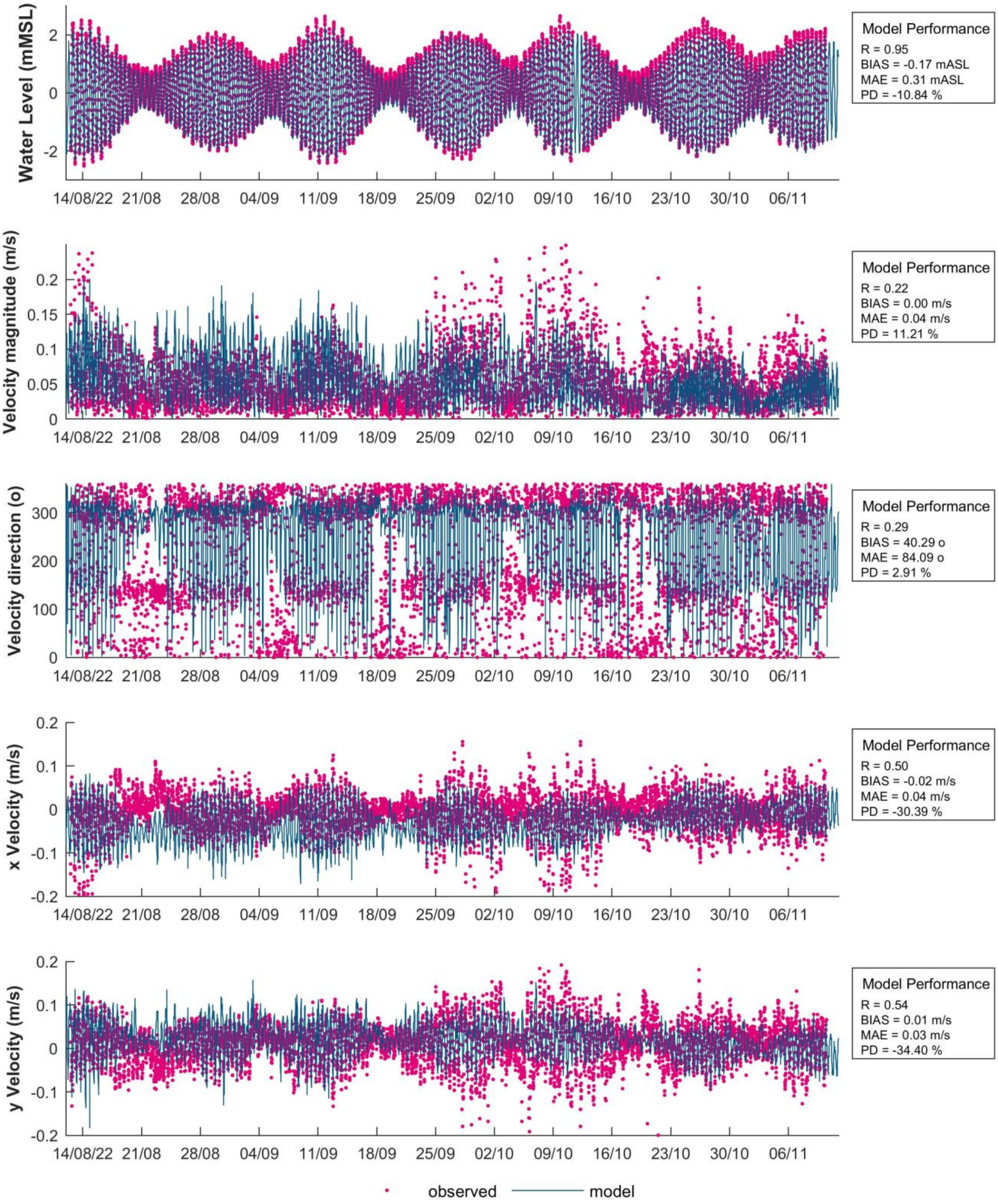


Figure 2.4 Model comparison to ADCP data at the bed (3 - 5 m above the seabed).

# 3 Dispersion modelling

## 3.1 Model

The impact of bath medicine footprints was represented as plumes of dissolved constituents with increased dilution from the point of treatment release. The dispersion of Azamethiphos following treatment has been simulated using a high-resolution calibrated TUFLOW FV hydrodynamic model, as described in Section 2. Water velocities in the region were simulated using a calibrated TUFLOW FV hydrodynamic model and released bath treatment simulated using the advection and dispersion module.

### 3.1.1 Advection/Dispersion of inert tracers

Inert tracers were used to simulate the advection and dispersion of bath treatment within the area of interest and further afield towards any sensitive receptors. The use of inert tracers is viewed as an efficient and accurate way to simulate the dispersion of Azamethiphos in a bath treatment system and assess compliance against regulatory guidelines.

## 3.2 SEPA Standards

When Azamethiphos is released into water, it stays in the water until it breaks down into non-toxic derivatives, for which a decay half-life of 5.6 days has been determined (SEPA 2023). According to SEPA regulatory framework, to ensure safety, two standards are used: one is applied three hours after any discharge, and the other is applied 72 hours after the final discharge in any treatment period. The model was used to assess if proposed treatment scenarios, based on realistic farm operation, complied with Environmental Quality Standards (EQSs) established by SEPA. In order to assess the 3-hour EQS, a single pen release simulation will be performed and the size of the area where the concentration exceeds 250 ng/L will be compared against the allowable mixing zone as calculated using BathAuto. The calculated ellipse area will be marked in the plot as a line. After 72 hours, the area exceeding 40 ng/L should not exceed 0.5 $km^2$, while the maximum concentration in the domain should not exceed 100 ng/L (maximum allowable concentration - MAC) (Table 3.1).

Predicted residual concentrations for a particular compound will be compared with EQSs over an Allowable Zone of Effects (AZEs). AZEs are defined as the area (or volume) of seabed or receiving water in which SEPA will allow some exceedance of a relevant EQS (SEPA 2005). Beyond the far-field allowable zone of effect, surrounding a fish farm, bath treatment chemical concentrations must not exceed the defined environmental quality standards. For Azamethiphos it is the lower of 0.5 $km^2$ or 2 % of loch area within 72 hours (SEPA 2008).

Table 3.1 Environmental Quality Standards (EQSs) for Azamethiphos (SEPA 2005, 2008)

| Standards for Azamethiphos Timescale | Standard (ng per litre) | Type |
|---|---|---|
| 3 hours | 250 | EQS |
| 72 hours | 40 | EQS |
| 72 hours | 100 | MAC |

### 3.3 Priority Marine Features

Priority Marine Features (PMF) close to the farm site are shown in Figure 3.1. These PMF sites have been extracted from Marine Scotland's National Marine Plan interactive (NMPi) maps (The Scottish Government 2023a, 2023b). Timeseries concentrations at these sites were extracted and analysed for bath treatment impact.

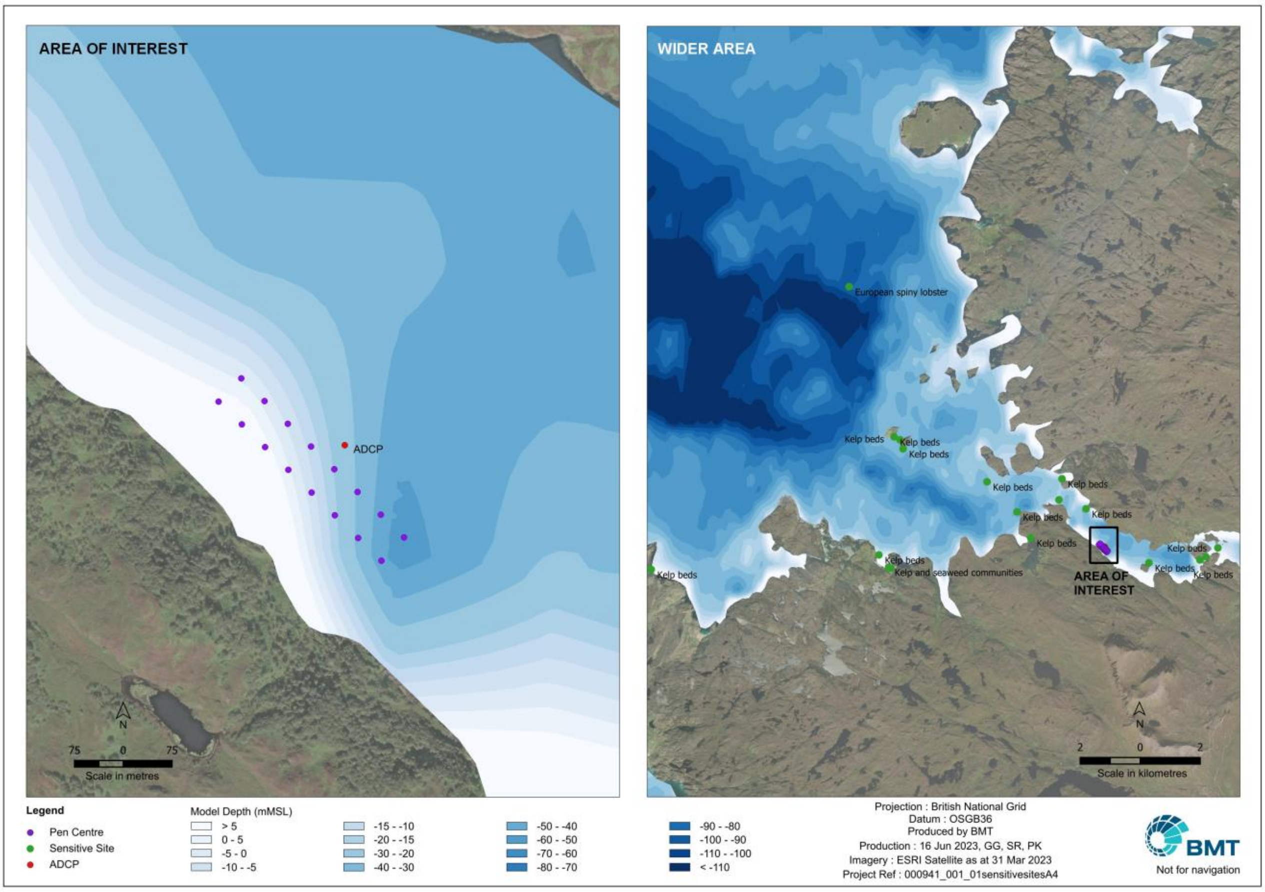


Figure 3.1 Pen centres with ADCP location (left) and nearby PMFs (right).

### 3.4 Simulation time periods

To simulate the worst-case condition, the dispersion modelling was initially conducted using TUFLOW FV flow fields over a period of two weeks centred on a small neap tidal range taken from the calibrated hydrodynamic model simulations. This was assumed to be the least dispersive set of ambient conditions, when Azamethiphos dispersion was least likely to meet the required EQS (See section 3.2). Simulations were also conducted during a two-week period of spring tides.

The two-week simulation period covered the duration of treatment, a dispersion period for the EQS assessment after 72 hours (long-term assessment as per guidelines) and an extra 24 hours to check for any chance concentration peaks. It has been identified that the medicines used in bath treatments are either rapidly broken down or bind to particles in the water rendering them unavailable to marine life. For this reason, short period simulations have been deemed sufficient to predict any potential impact (SSFL 2011).

Two tracer simulations were carried out for two distinct periods representative of neap and spring tide conditions extracted from the 90-day model calibration period in 2022:

- Neap tide model period (Figure 3.2):

  The tracer dispersion model was initiated on 13/10/2022 00:00 and ends 30/10/2022 00:00. The last treatment is administered on 19/10/2022 04:00:00, corresponding to the smallest maxima of the neap tidal cycle, where the final treatment is released at highwater.

- Spring tide model period (Figure 3.3):

  The tracer dispersion model was initiated on 06/09/2022 00:00 and ends 22/09/2022 00:00. The last treatment is administered on 11/09/2022 20:00:00, corresponding to the highest maxima of the spring tidal cycle, where the final treatment is released at highwater.

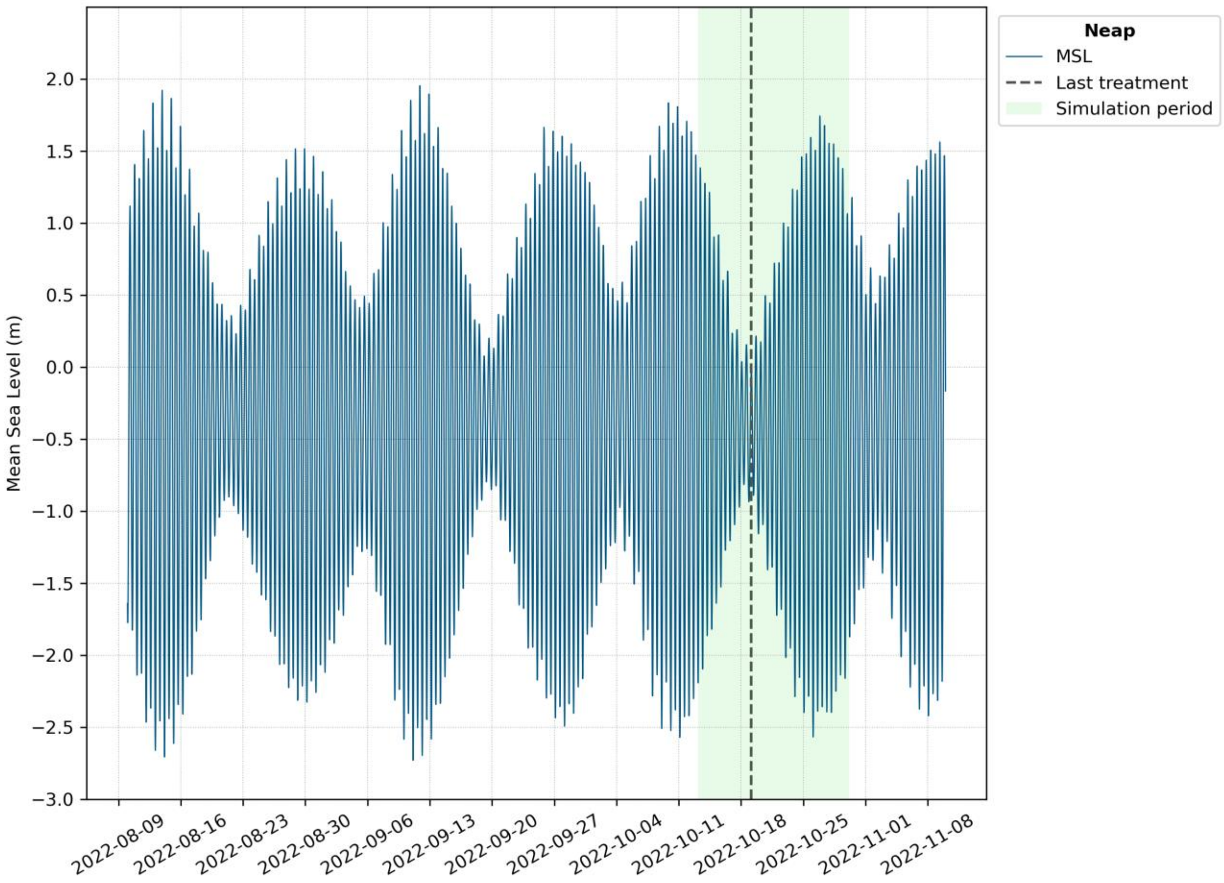


Figure 3.2 Neap simulation period: The smallest neap maxima was on 19/10/2022 04:00:00.

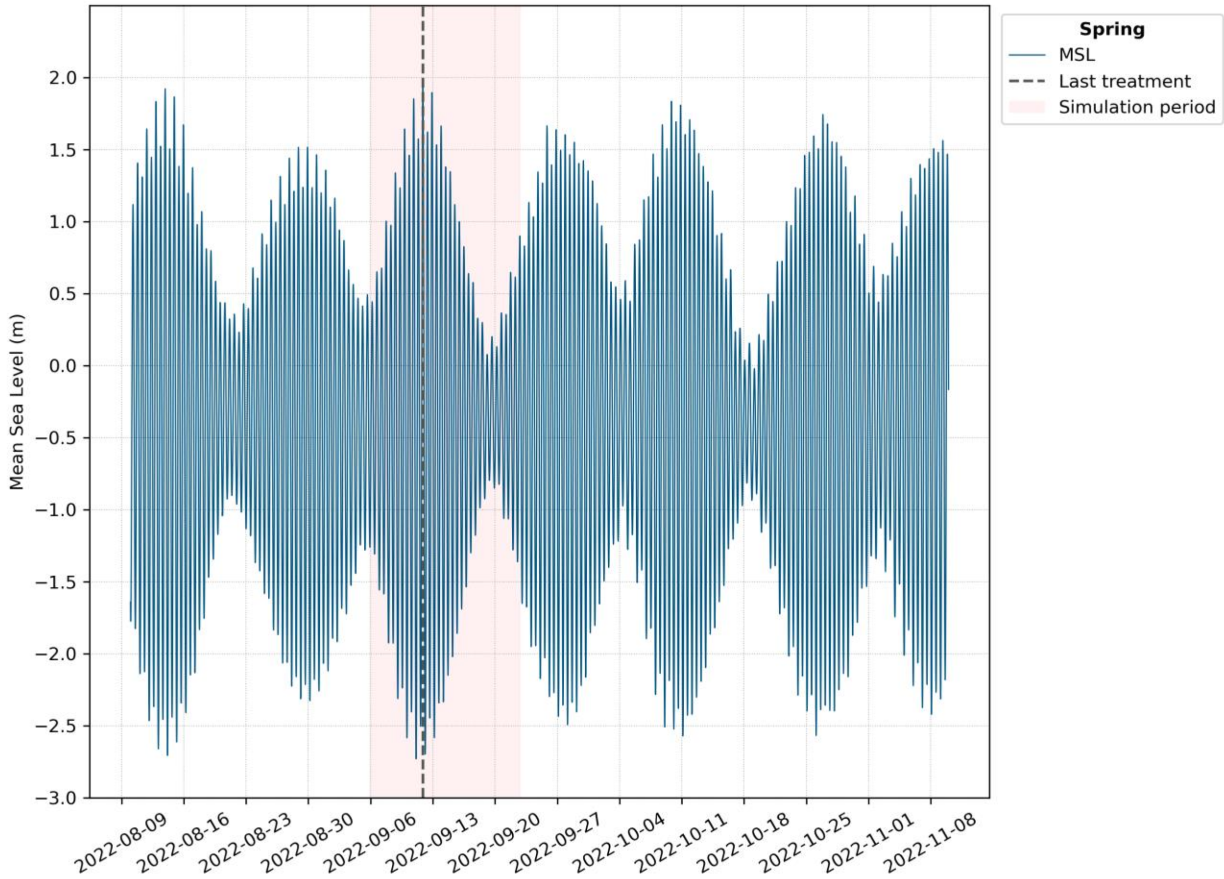


Figure 3.3 Spring simulation period: The highest spring maxima was on 11/09/2022 21:20:00.

## 3.5 Bath treatment

### 3.5.1 Dosage and schedule

The method of bath treatment was simulated by applying 230 g of Azamethiphos to each pen with releases at multiple times per day (three times per day with 3 hourly intervals) (Pers com. Loch Duart) to represent a realistic daily treatment campaign. A total of 3.68 kg of Azamethiphos was discharged over the six-day period. The order of pens treated in this scenario is shown in Figure 3.4. The treatment schedule was designed with consideration to the time needed for setting up each treatment, moving between pens, and the duration of the treatment. The Azamethiphos treatment was modelled as a tracer released over a period of 5 minutes spread over the surface 4 m of the water column to represent the release of the treatment when the bath volume is released. Table 3.2 and Table 3.3 present the simulated tracer release times and order for all pens in the farm during both neap and spring tide scenarios.

Azamethiphos discharge was included as a point source boundary condition with specifications of location coordinates of pens, discharge rate, temperature, salinity, and bath treatment schedule with concentrations or mass of the Azamethiphos as determined by Loch Duart. The 3 hr EQS only considered a single release, while the 72 hr EQS and MAC considered all releases.

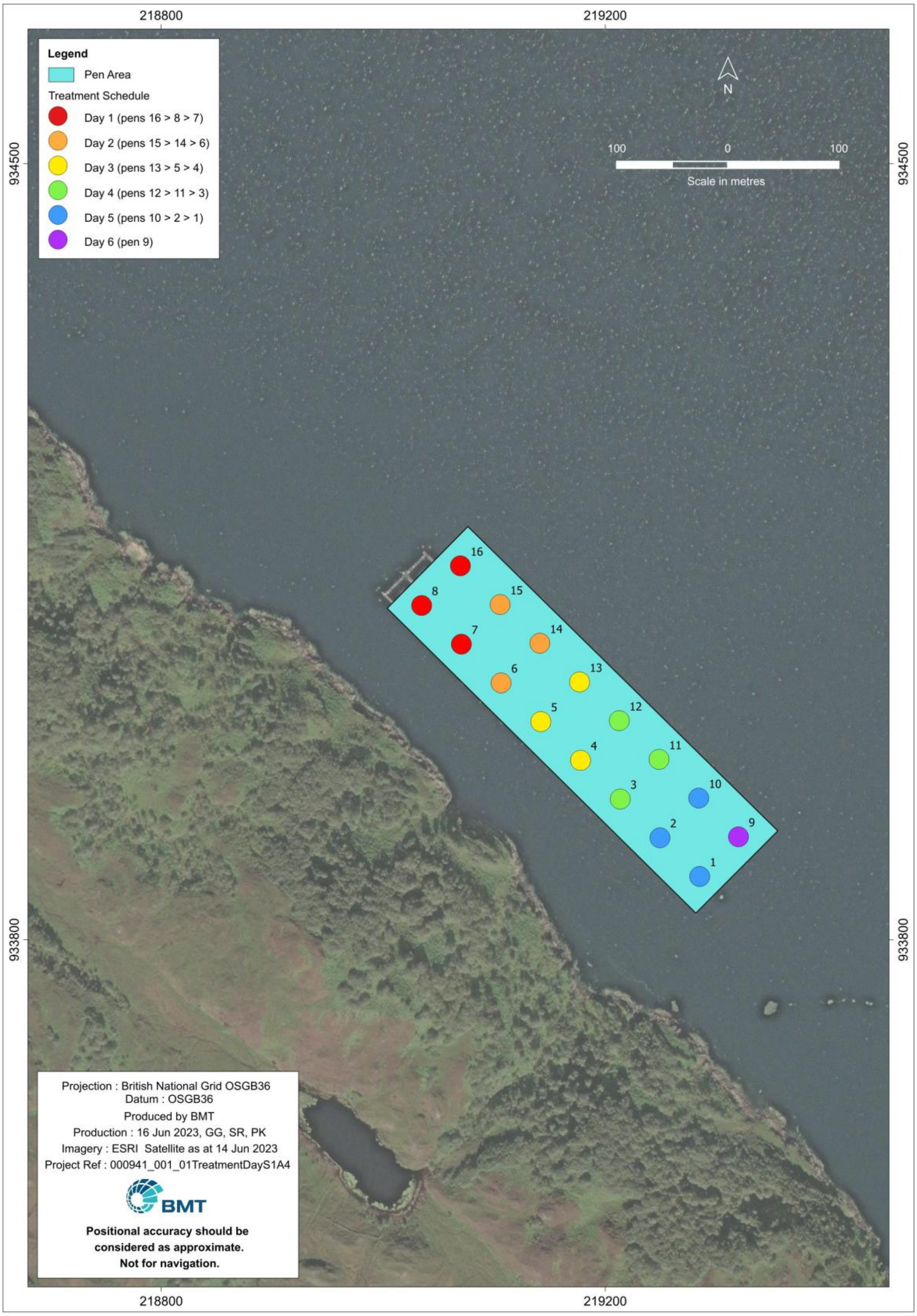


Figure 3.4 Bath treatment order.

Table 3.2 Treatment schedule for the neap tide simulation period.

| Day | Date | Time | Pen # |
|---|---|---|---|
| 1 | 14/10/2022 | 4:00:00 | 16 |
| 1 | 14/10/2022 | 7:00:00 | 8 |
| 1 | 14/10/2022 | 10:00:00 | 7 |
| 2 | 15/10/2022 | 4:00:00 | 15 |
| 2 | 15/10/2022 | 7:00:00 | 14 |
| 2 | 15/10/2022 | 10:00:00 | 6 |
| 3 | 16/10/2022 | 4:00:00 | 13 |
| 3 | 16/10/2022 | 7:00:00 | 5 |
| 3 | 16/10/2022 | 10:00:00 | 4 |
| 4 | 17/10/2022 | 4:00:00 | 12 |
| 4 | 17/10/2022 | 7:00:00 | 11 |
| 4 | 17/10/2022 | 10:00:00 | 3 |
| 5 | 18/10/2022 | 4:00:00 | 10 |
| 5 | 18/10/2022 | 7:00:00 | 2 |
| 5 | 18/10/2022 | 10:00:00 | 1 |
| 6* | 19/10/2022 | 4:00:00 | 9 |

***Final treatment was based on the smallest maxima for the neap tide.**

Table 3.3 Treatment schedule for the spring tide simulation period.

| Day | Date | Time | Pen # |
|---|---|---|---|
| 1 | 6/09/2022 | 21:20:00 | 16 |
| 1 | 7/09/2022 | 12:20:00 | 8 |
| 1 | 7/09/2022 | 3:20:00 | 7 |
| 2 | 7/09/2022 | 21:20:00 | 15 |
| 2 | 8/09/2022 | 12:20:00 | 14 |
| 2 | 8/09/2022 | 3:20:00 | 6 |
| 3 | 8/09/2022 | 21:20:00 | 13 |
| 3 | 9/09/2022 | 12:20:00 | 5 |
| 3 | 9/09/2022 | 3:20:00 | 4 |
| 4 | 9/09/2022 | 21:20:00 | 12 |
| 4 | 10/09/2022 | 12:20:00 | 11 |
| 4 | 10/09/2022 | 3:20:00 | 3 |

| Day | Date | Time | Pen # |
|---|---|---|---|
| 5 | 10/09/2022 | 21:20:00 | 10 |
| 5 | 11/09/2022 | 12:20:00 | 2 |
| 5 | 11/09/2022 | 3:20:00 | 1 |
| 6* | 11/09/2022 | 21:20:00 | 9 |

***Final treatment was based on the highest maxima for the spring tide.**

### 3.5.2 Decay rate

A half-life of 5.6 days was applied to represent Azamethiphos decay (SEPA 2023), this equated to the time required for half of the substance to decay (equivalent to a decay rate of 0.12377 per day).

### 3.5.3 Horizontal scalar diffusivity

In TUFLOW-FV, the horizontal scalar diffusivity refers to the horizontal diffusion coefficient that is used to calculate the rate at which a scalar quantity, such as temperature or concentration, is mixed and transported in the horizontal direction due to turbulent eddies and mixing processes (TUFLOW 2017, 2018).

The horizontal scalar diffusivity is typically calibrated using field data or laboratory experiments to ensure that it accurately represents the actual horizontal diffusion properties of the fluid being modelled. For this exercise, selection of global horizontal scalar diffusivity has been guided by dye releases conducted near the Reintraid site by Anderson Marine Surveys Ltd in April 2023 (Anderson Marine Surveys 2023). According to the dye patch study, from a total of 97 transects over the four Reintraid releases, the measured Fickian diffusivity varied from 0.004 – 0.355 $m^2$/s, with a mean of 0.023 $m^2$/s and median of 0.058 $m^2$/s. Thus, for the base model these field measurements were adapted. The area of interest, approximately a 10 m radius from the farm centre, and the entire model domain had a uniformly applied global horizontal scalar diffusivity limit of 0.004 - 0.355 $m^2$/s and 0.004 – 9999 $m^2$/s, respectively. The global vertical scalar diffusivity limit of 0.0 - 1.0 $m^2$/s was uniformly applied to the whole model domain. Typical reported values for horizontal dispersion component measured using dye patch studies in coastal waters varies widely (e.g. from 0.02 – 2.17 $m^2$/s; Anderson Marine Surveys 2023, Elliott et al 1997, Morales et al 1997).

### 3.5.4 Vertical scalar diffusivity

The vertical scalar diffusivity refers to the vertical diffusion coefficient calculated within TUFLOW, based on limits specified in the model configuration file. For the dispersion modelling base runs, we used a standard limit of 0 – 1. The global vertical scalar diffusivity limits for TUFLOW FV represent a range of possible values for the vertical scalar diffusivity, rather than a specific value. The lower limit of '0' means that the vertical scalar diffusivity must be greater than zero, while the upper limit of '1' represents the maximum value of the vertical scalar diffusivity that can be used in the model.

In the absence of a specific value for the vertical scalar diffusivity, it is common practice to use a range of values that are considered reasonable for the specific aquatic system being modelled, based on available data and knowledge of the system. In the absence of a specific value for the vertical scalar diffusivity, the TUFLOW-FV model calculates the actual values of the vertical scalar diffusivity during the simulation based on the local flow and turbulence conditions, subject to the constraint of the global vertical scalar diffusivity limits specified. The model does not use the maximum value of the global vertical scalar diffusivity limit as the default value, but instead uses the calculated values that fall within the specified range.

The selection range of appropriate values for the vertical scalar diffusivity can affect the accuracy of the model results, making it necessary to perform sensitivity analyses to the vertical scalar diffusivity within the specified range.

The Smagorinsky model calculates the eddy viscosity and diffusivity coefficients based on the local flow conditions and the rate of strain of the flow (TUFLOW 2017, 2018). These coefficients are then used to calculate the vertical scalar diffusivity at each computational cell and time step.

#### 3.5.5 Mass Balance

To assess mass balance and the effects of numerical dispersion, 100 mg of tracer mass was released at the two ocean boundaries, while maintaining the initial concentration of the tracer at 100 mg/L throughout the model domain. The model was simulated for 4 months (01/05/2022 to 01/09/2022), with zero tracer decay rates. Timeseries of volume, tracer mass, and concentration within the model domain were analysed.

# 4 Results

## 4.1 Modelled Flow Fields

Figure 4.1 illustrates the flow dynamics within the Loch a' Chairn Bháin flow region during peak spring-neap, flood, and ebb tides. The flow experiences constraints and acceleration as it approaches the topographical constriction closer to the loch entrance, specifically near Duartmore bay. Additionally, on the east side of the farm, close to the Kylesku bridge, accelerated flow is observed due to the presence of narrow morphological features within the loch. In these particular areas, velocities can reach up to 3 m/s, whereas near the farm area, velocities remain relatively low, hardly exceeding 0.3 m/s throughout the tide cycles.

## 4.2 EQS – 3 hr

To assess the short-term compliance for Azamethiphos, a single tarpaulin release of a 3-hour mass (230 g) is modelled. Figure 4.2 and Figure 4.3 show the area covered by the plume that exceeds a concentration of 250 ng/L within the top 4 m of the water column following the initial release (at 0 hours on the x-axis), for the neap and spring tides, respectively. The size of the area where the concentration exceeds 250 ng/L was compared against the allowable mixing zone as calculated using BathAuto. For this exercise, the ellipse area (mixing zone) calculated by BathAuto is 0.0537 km² (TransTech Limited 2023b) and this ellipse area was marked in the plot as a line. In both cases, the size of the chemical plume after a single treatment is well below the calculated ellipse area after 3 hours.

During the neap tide simulation, the tracer area exceedance reached its highest point at approximately 0.01059 km² after 1.6 hours from the initial release. Throughout the neap tide period, the area greater than 250 ng/L remained below the EQS area, indicating no breach of the EQS threshold. With the area after 3-hours (the EQS time) corresponding to zero.

In contrast, during the spring tide scenario, the plume greater than 250 ng/L reached its maximum extent at approximately 0.0360 km² after 1 hour from the initial release. This is less than the calculated mixing area of 0.0537 km², and after 1.6 hours the dispersion area corresponds to zero, signifying that the plume's area never exceeded the EQS threshold, accounting for 0 % of the total EQS area.

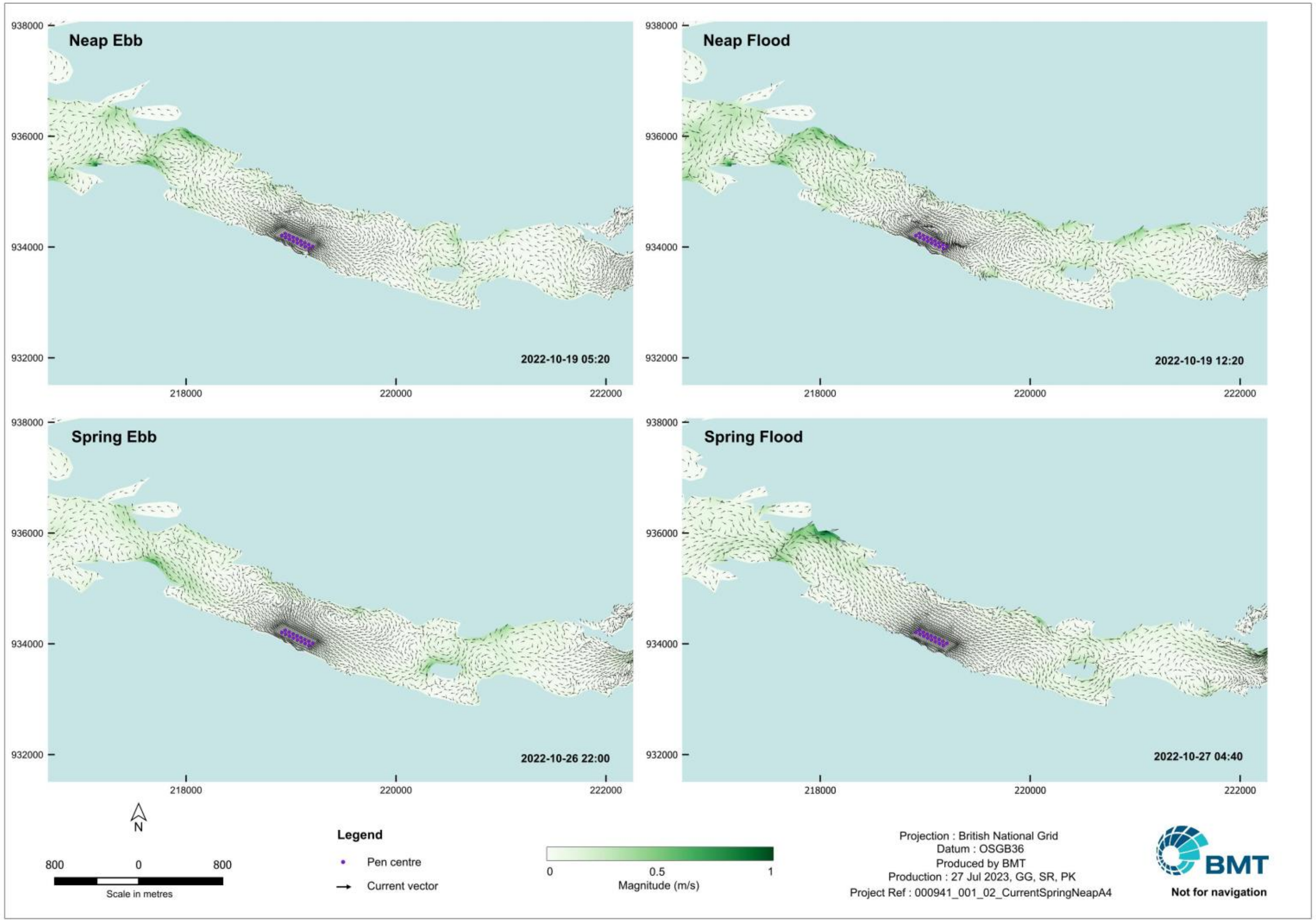


Figure 4.1 Modelled flow field across Loch a’ Chairn Bháin at peak flooding and ebbing tides for the spring-neap tidal cycle. Grey lines represent flow vectors.

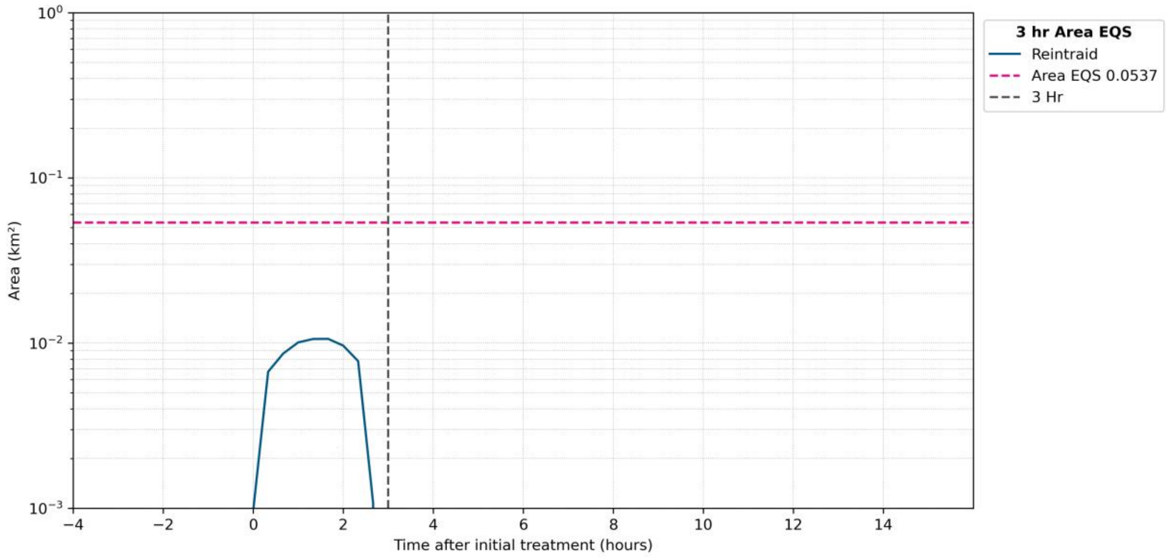


Figure 4.2 Neap tide area exceeding 3 hr EQS value (250 ng/L).

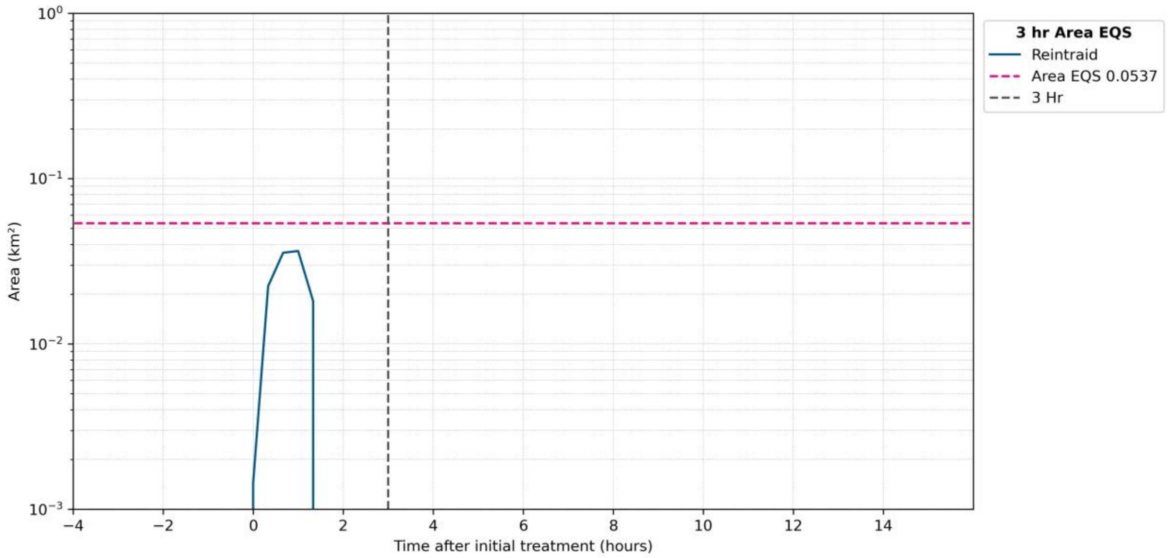


Figure 4.3 Spring tide area exceeding 3 hr EQS value (250 ng/L).

### 4.3 Maximum Allowable Concentration (MAC) – 72 hr

The SEPA standards state that after 72 hours the maximum concentration of Azamethiphos must be less than 100 ng/L (Section 3.2).

To assess the long-term risks from Azamethiphos, the full treatment regime is modelled. This simulated an individual treatment mass of 230 g, resulting in a maximum 24 hr treatment mass of 690 g, and a total treatment regime of 3.68 kg over 6 days. The depth-averaged maximum concentration within the whole water column for the neap and spring tide cycles are plotted in Figure 4.4 and Figure 4.5 respectively.

The individual pen treatments are recognisable by the sharp peaks in maximum chemical concentrations. The chemical mass is introduced rapidly into the model domain creating a steep increase; following this, decay and dispersion causes a rapid decrease in peak concentrations. Under neap tide conditions, the concentration from the proposed site at 72 hours after the final treatment measures 6.02 ng/L, equivalent to 6.02 % of the MAC value. On the other hand, during the spring tide, at 72 hours after the final treatment, the concentration from the proposed site is 3.71 ng/L, which corresponds to 3.71 % of the MAC value. Following the final treatment, a general decline in the maximum concentration was observed for both spring and neap tides.

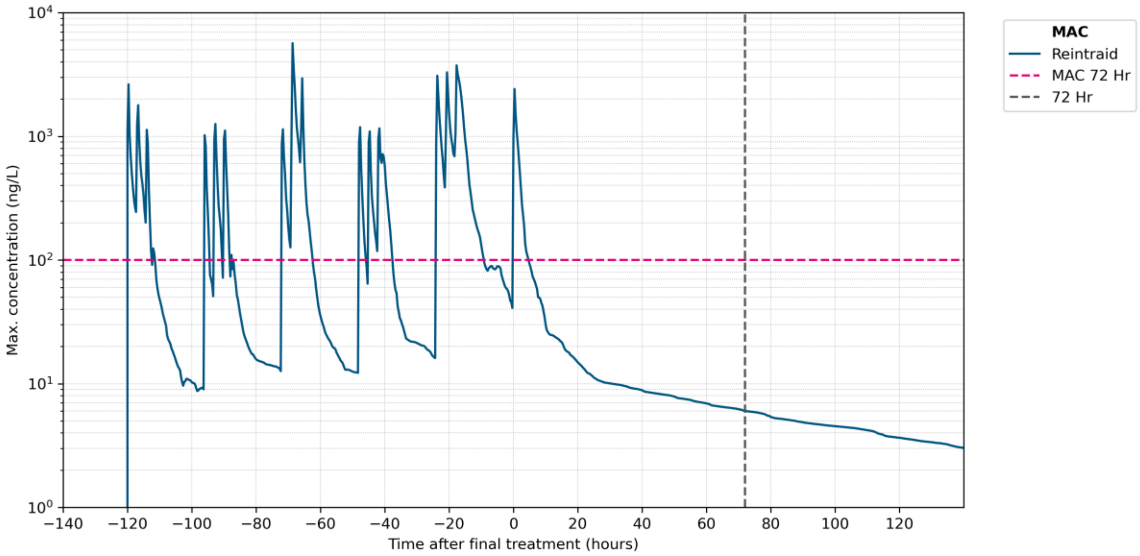


Figure 4.4 Maximum concentration of Azamethiphos during neap tide release.

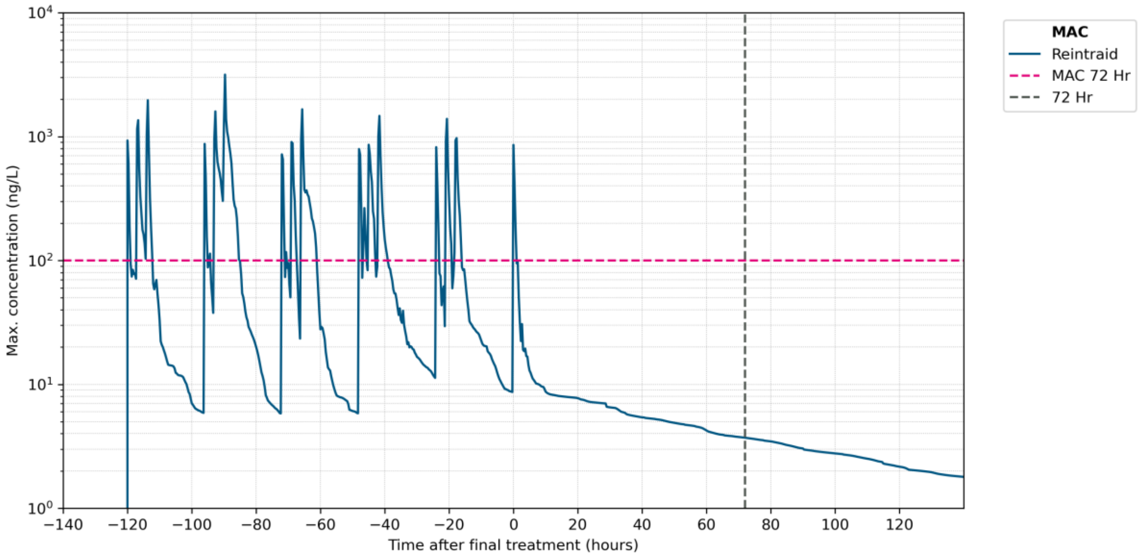


Figure 4.5 Maximum concentration of Azamethiphos during spring tide release.

## 4.4 EQS – 72 hr

The SEPA standards state that 72 hours after the final release the area of the plume that exceeds 40 ng/L must be less than 0.5 km² (Section 3.2).

The area of the chemical plume exceeding a concentration of 40 ng/L (72-hour EQS) within the top 4 m of the water column is plotted in Figure 4.6 and Figure 4.7. For both the neap and the spring conditions, the area greater than 40 ng/L never exceeded 0.5 km².

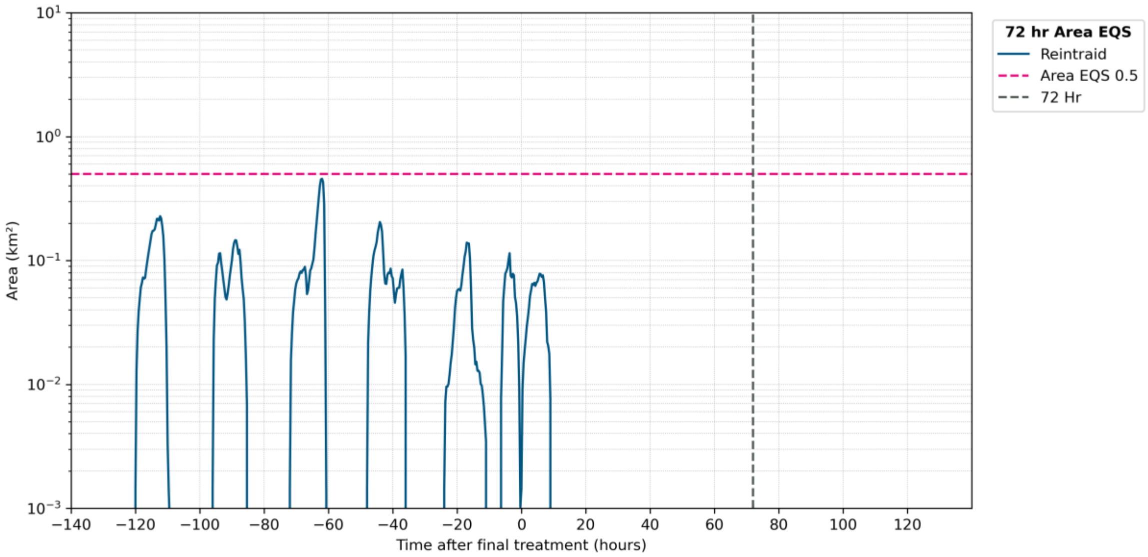


Figure 4.6 Neap tide area exceeding 72 hr EQS value (40 ng/L).

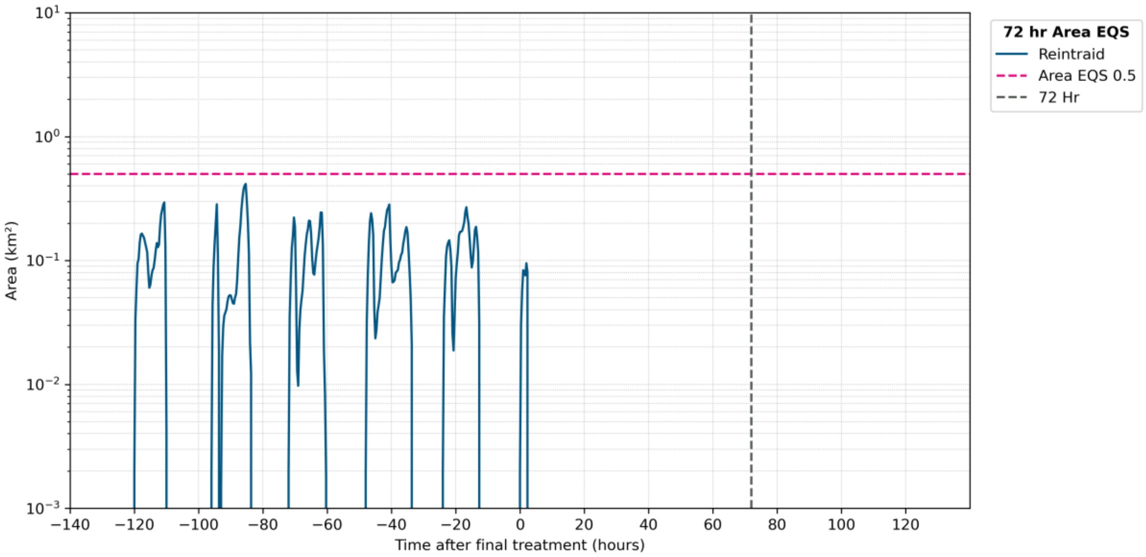


Figure 4.7 Spring tide area exceeding 72 hr EQS value (40 ng/L).

## 4.5 Spatial distribution

Figure 4.2 and Figure 4.3 show the spatial distribution of Azamethiphos treatments (depth-averaged concentrations) during neap and spring tides, respectively. At the 3-hour mark, the discharge from a single pen, results in limited coverage below the EQS value (250 ng/L) predominantly on the western side of the farm during neap and spring tide conditions. Although these areas are temporary, they have not had adequate time to dissipate from their initial treatment location. By the 72-hour mark, the majority of bath treatment plumes have dispersed, falling below the EQS threshold (40 ng/l) for both neap and spring tides. This indicates that the dispersion and dilution processes have effectively mitigated any potential adverse impacts, leading to plumes that comply with the EQS standards.

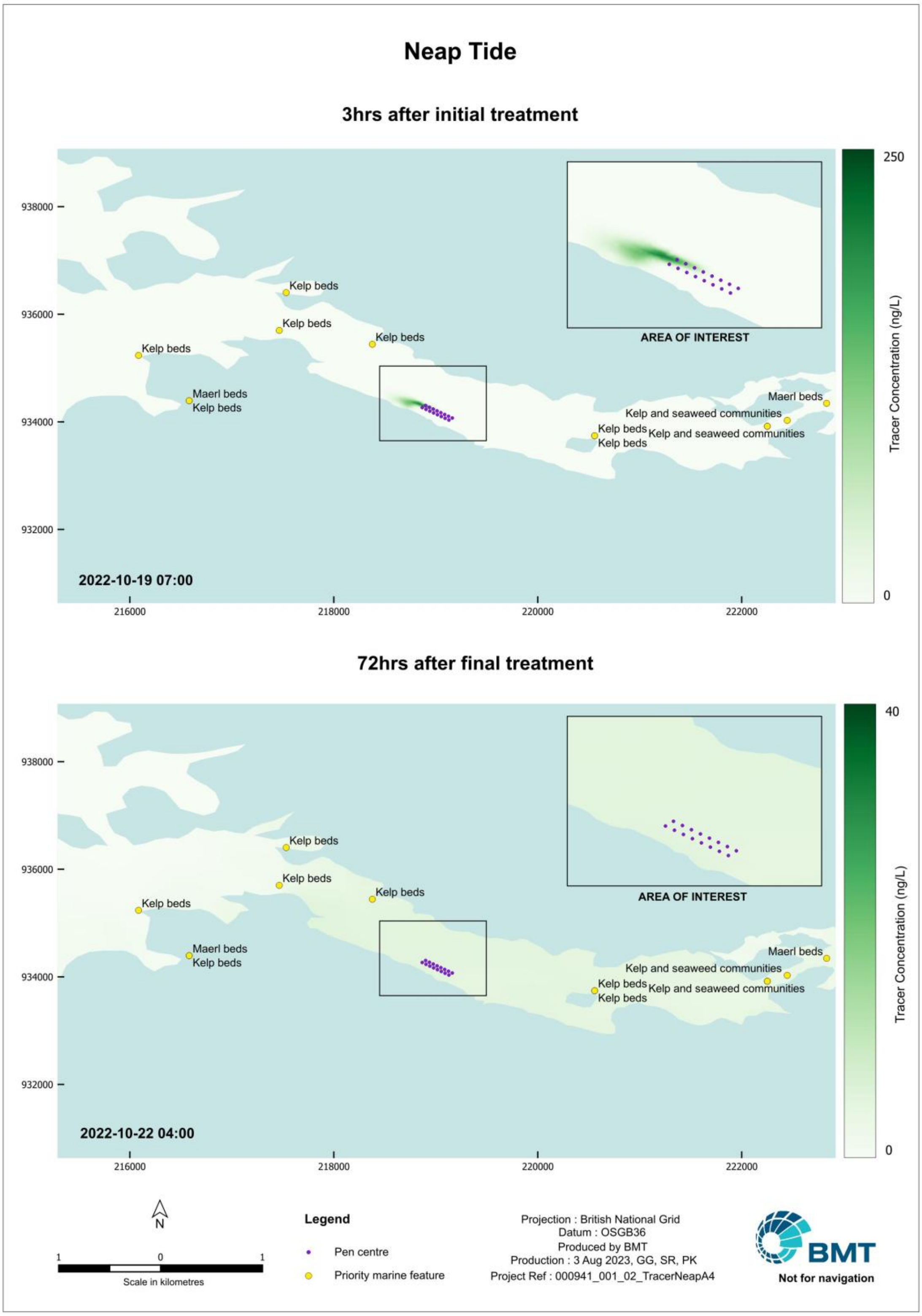


Figure 4.8 Spatial Azamethiphos distribution for tarpaulin release during neap tides, 3 hr after the initial 3-hour mass release (top) and 72 hr after the last treatment event (bottom).

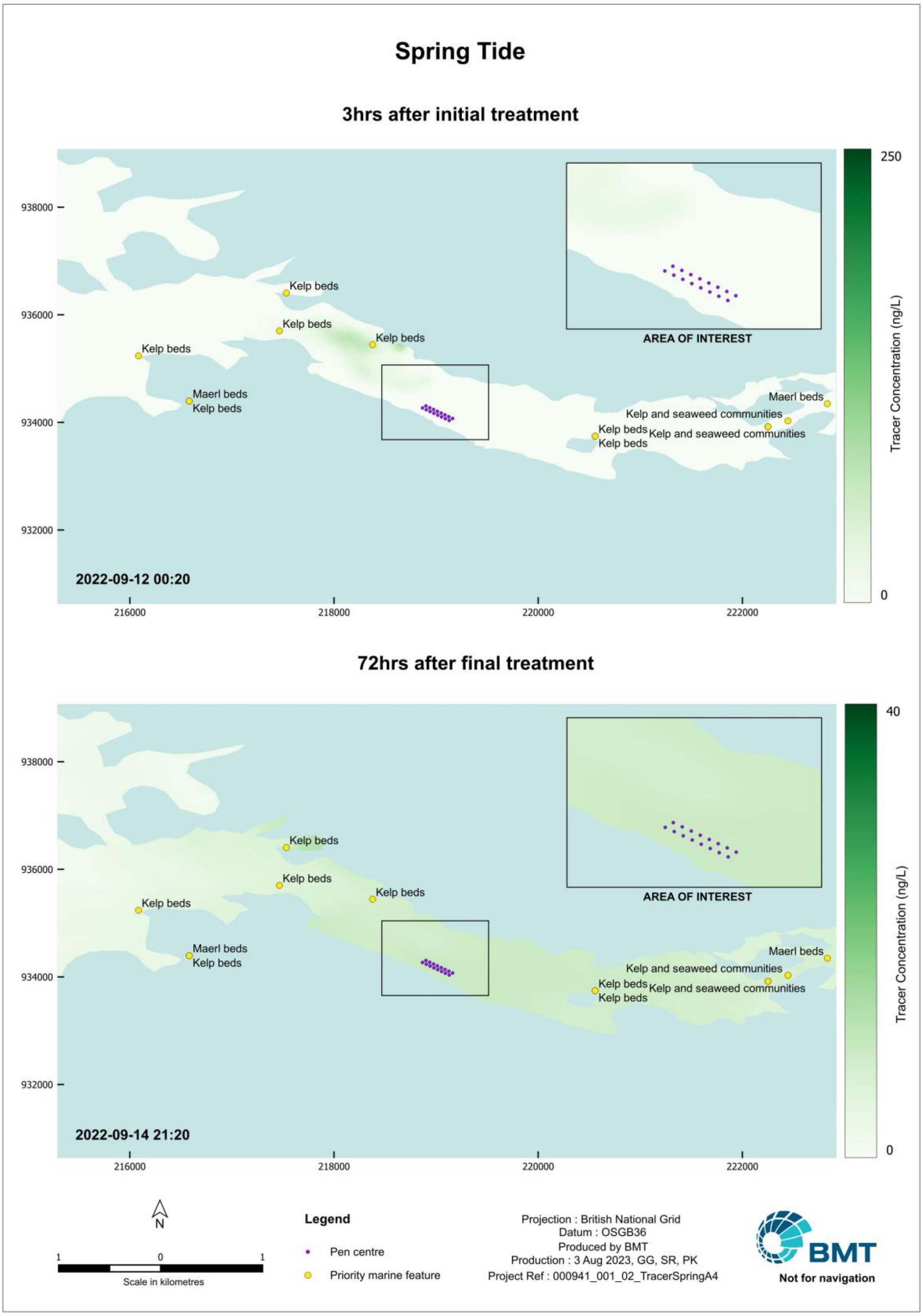


Figure 4.9 Spatial Azamethiphos distribution for tarpaulin release during spring tides, 3 hr after the initial 3-hour mass release (top) and 72 hr after the last treatment event (bottom).

## 4.6 Priority Marine Features

The model predicted concentrations at all PMF sites within the model boundary, including those closest to the Reintraid farm were well below the 72 hr EQS (of 40 ng/L). The closest four PMFs include two from the east side of the farm and two from the west side of the farm, These were plotted with timeseries chemical concentration during the neap tide for both the depth-averaged bottom 1 m  and the depth-averaged surface 1 m (Figure 4.10). The four PMFs site details are as follows (see section 3.3 for more details):

- Kelp beds #49925 – approximately 1.3 km west from the farm,
- Kelp beds #49931 – approximately 1.4 km east from the farm,
- Kelp beds #499368 – approximately 2.1 km west from the farm,
- Maerl beds #49555 – approximately 3.1 km east from the farm.

At all sites including kelp beds, seaweed communities and maerl beds selected as 'PMFs or sensitive habitats nearby', the predicted Azamethiphos concentrations never exceeded 40 ng/L at any given time. Note that plots for all the nearby sites were not included in the report however can be supplied upon request.

Further, the same sites were plotted for the chemical concentration during the spring tide for the bottom 1 m (depth-averaged) and the surface 1 m (depth-averaged) (Figure 4.11). At all sites including kelp beds, seaweed communities and maerl beds selected as 'PMFs or sensitive habitats nearby', the predicted Azamethiphos concentrations don't exceed 40 ng/L after 72 hrs. Note that plots for all the nearby sites were not included in the report however can be supplied upon request.

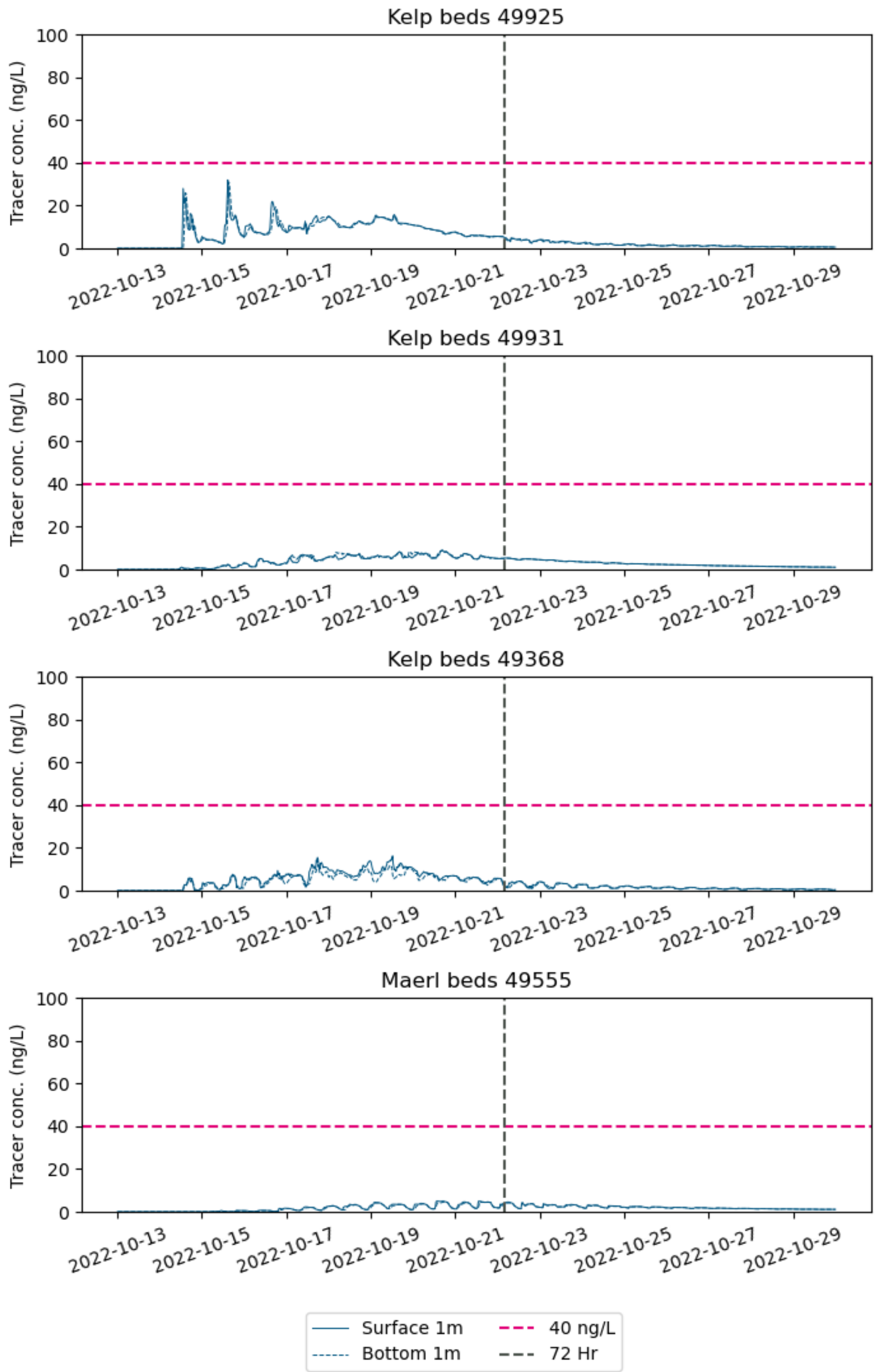


Figure 4.10 Tracer concentration at the four closest PMF sites; surface 1 m (solid) and bottom 1 m (dashed) depth averaged tracer concentrations, compared during neap tide.

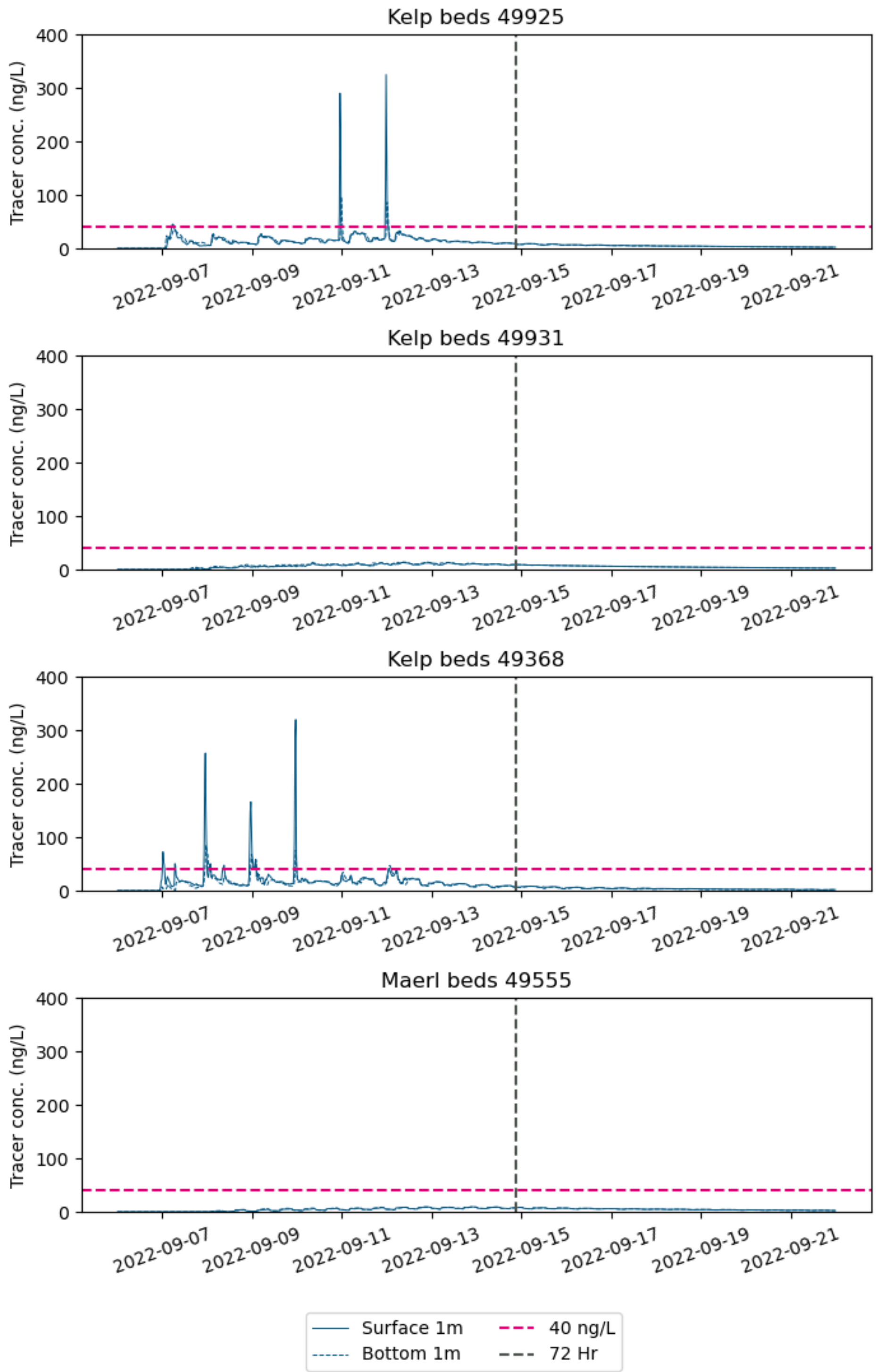


Figure 4.11 Tracer concentration at the four closest PMF sites; surface 1 m (solid) and bottom 1 m (dashed) depth averaged tracer concentrations compared during spring tide.

## 4.7 Sensitivity Analysis

A sensitivity analysis was undertaken to ensure that the model parameter values chosen do not have an effect on the overall result of the compliance assessment. The sensitivity analysis was performed on the neap tide, as this is the theoretical worst-case simulation. Timeseries of AZE (allowable zone of effects) plotted with the 72 hr EQS (area with a concentration greater than 40 ng/L should be less than 0.5 $km^2$), for the full treatment regime, are used for comparisons.

### 4.7.1 Horizontal scalar diffusivity

Out of a total of 97 transects conducted during the four Reintraid releases, the measured Fickian diffusivity exhibited a range of 0.004 to 0.355 $m^2/s$. Consequently, this range was employed for establishing the base model simulations. Notably, in the region of interest encompassing the three locations of dye releases, measured horizontal diffusivity, K, is comparable to the default value of 0.1 $m^2/s$ (mean 0.072 $m^2/s$, median 0.029 $m^2/s$, range 0.004 - 0.745 $m^2/s$). 22.7 % of measured values exceeded 0.1 $m^2/s$; 77.3 % were below this default value (Anderson Marine Surveys 2023).

Hence, guided by the findings of the dye study, three specific values—0.004, 0.029, and 0.745—were selected for the sensitivity testing of horizontal scalar diffusivity. These values were then compared with the baseline simulation's horizontal diffusivity range of 0.004 to 0.355. The timeseries of area exceeding 40 ng/L (Figure 4.12) shows the differences for the three horizontal scalar diffusivities. Across values, the difference is negligible, and the mean value (0.029 $m^2/s$) line plot is the closest one to the base line simulation.


Figure 4.12 Timeseries of area exceeding 40 ng/L in the surface 4 m depth averaged, from final treatment release, comparing a range of horizontal scalar diffusivity values.

### 4.7.2 Vertical scalar diffusivity

We have used two vertical scalar diffusivity limits for the sensitivity analysis:

- 0 - 1 This limit was used for all the dispersion base model runs.
- 1 - 9999 To allow an increased vertical diffusion for the sensitivity analysis.

The timeseries of tracer concentration (Figure 4.13) show some variations between the two limits. However, this disparity is not substantial enough to breach the EQS, even when considering the comparatively higher vertical diffusivity limits. This suggests that the assessment is independent of vertical scalar diffusivity limit chosen.

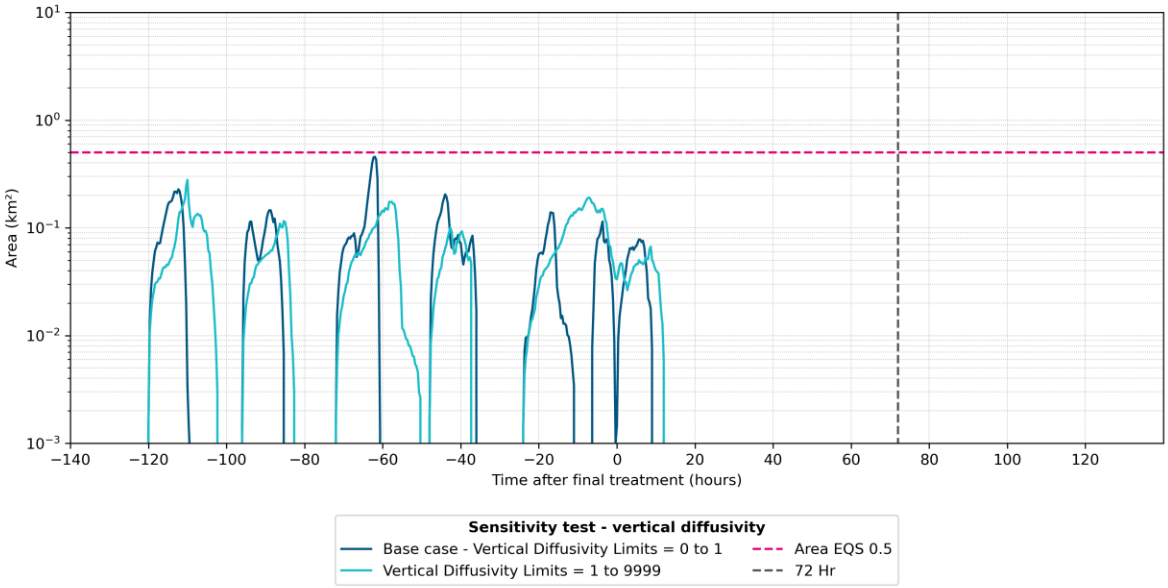


Figure 4.13 Timeseries of area exceeding 40 ng/L in the surface 4 m depth averaged, from final treatment release, comparing two vertical scalar diffusivity limits.

### 4.7.3 Time of release

Varying the time of release by +/- 6 and 3 hours was included to ensure a range of bath treatment release times relating to tidal cycles were tested for sensitivity in results.

The predicted AZE timeseries (Figure 4.14) show the results from the different release times. Note the x axis of this plot is in hours based on the base case - neap tide simulation where 0 falls on the final treatment time (‘0 hours line’). Although small differences can be seen between the results, the overall exceedance assessment is the same, with all sensitivity test results predicting concentrations below the EQS within 72 hours of the last treatment.

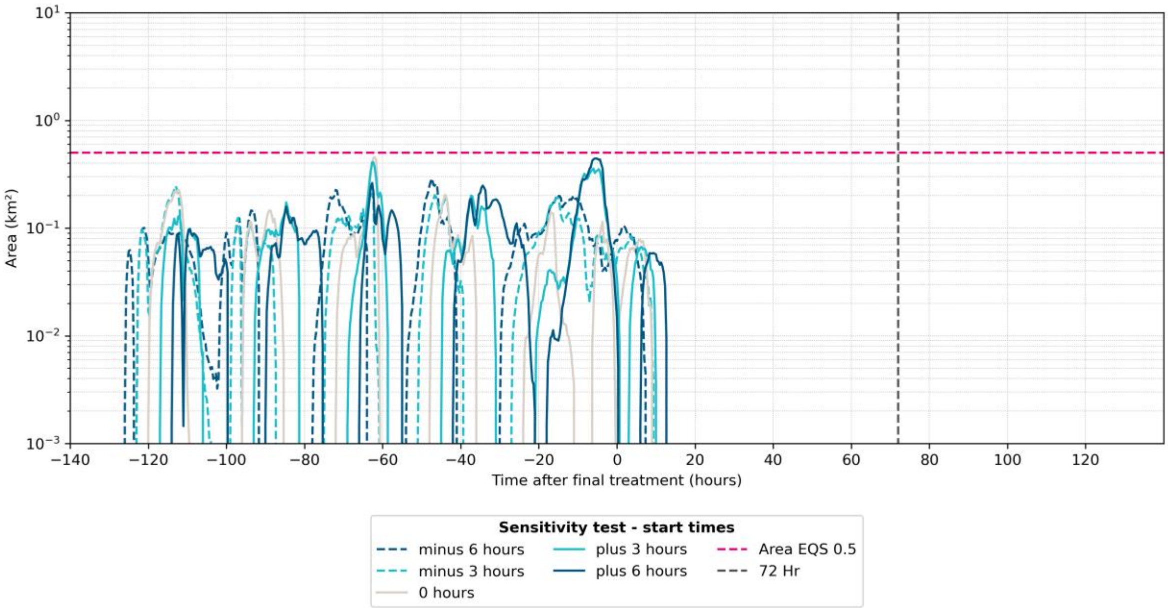


Figure 4.14 Timeseries of area exceeding 40 ng/L in the surface 4 m depth averaged, from final treatment release, comparing the start times.

## 4.8 Mass balance

During the four-month simulation of the mass balance analysis (Figure 4.15), we plotted the tracer volume, mass, and concentration. The results revealed that the residual tracer concentration remained negligible, accounting for less than 2 % throughout the entire four-month period. These findings provide strong evidence supporting the accuracy and reliability of the simulation. They also confirm that mass conservation is effectively maintained within the computational domain during the advection-dispersion calculations.

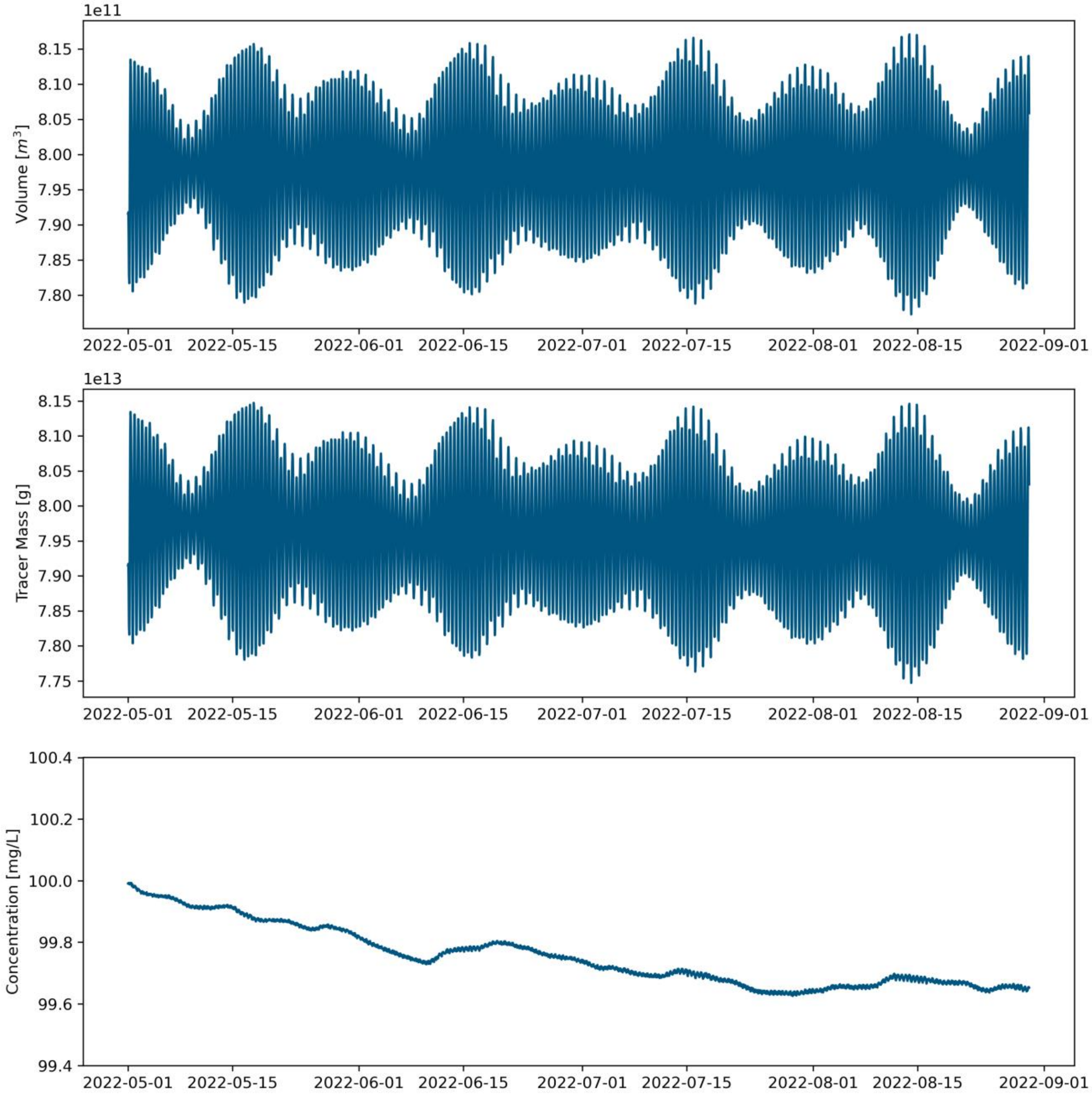


Figure 4.15 Mass balance plots for volume, tracer mass and tracer concentration in the model domain.

# 5 Conclusions

This technical report outlines the simulation of bath treatment chemical 'Azamethiphos' at the proposed Reintraid site, with a focus on addressing concerns related to Priority Marine Features (PMFs) as raised by SEPA in their 2021 screening modelling and risk identification report (SEPA 2021). Additionally, the report aims to derive appropriate bath chemical quantities compliant with EQS standards.

The application of a calibrated hydrodynamic model allowed for the simulation of bath treatments at the proposed site. Reasonable agreement with observed data for water level and velocity including x and y velocity components was achieved during hydrodynamic model calibration.

To investigate bath treatment dispersion, tracers were released from pen sites, driven by the calibrated hydrodynamic model. The dispersion model was then utilised to assess environmental compliance during the use of Azamethiphos as a bath treatment chemical. Tracer releases were designed to replicate realistic treatment regimes, with three treatments per day at a 3-hour interval. To represent a worst-case scenario, neighbouring pens were consecutively treated with 230 g of Azamethiphos per treatment (daily total 690 g) over five consecutive days, with the final pen treated on day six. The total amount of Azamethiphos discharged over the six-day period was 3.68 kg.

The simulations were conducted for release during neap and spring tides, while varying diffusion coefficients and time of release start time to assess the sensitivity of the outcomes to key model parameters.

Based on the model results, it was concluded that the proposed treatment scenarios, involving 230 g per pen with up to three pens treated per day (daily total 690 g), were predicted to consistently meet all EQS as prescribed by SEPA. The maximum concentration observed during the baseline simulations, 72 hours after the final treatment, was found to be less than 13 ng/L, well below the allowable limit. Additionally, predicted AZEs for EQS of 40 ng/L were zero for both spring and neap tide conditions within 72 hours of the final treatment. The sensitivity tests performed on horizontal diffusivity, vertical diffusivity, and starting times consistently indicate that the predicted chemical concentrations meet the EQS criteria. During spring tides, a slightly greater chemical dispersion was observed compared to neap tides. However, concentrations exhibited a significantly faster rate of decrease during spring tides as opposed to neap tides. In both neap and spring scenarios, the predicted chemical levels consistently meet the EQS criteria. The numerical simulation of bath treatments has shown successful treatment options using Azamethiphos, with the application of these treatments being compliant with EQS.

As part of the analysis of dispersion model simulations, the impact of bath treatments on Priority Marine Features (PMFs) in the wider area around the farm was investigated. The concentration levels of Azamethiphos were assessed during and after treatments, and it was found that they never exceeded the permissible limit. Additionally, the concentration values remained below 40 ng/L at the 72 hr mark from the final treatment at all PMFs located near the farm.

The hydrodynamic tracer models used in this study have provided valuable insights, demonstrating the safe and compliant application of bath treatments using Azamethiphos at the proposed Reintraid site. In conclusion, the results indicate that the proposed treatment option of Azamethiphos, involving a daily release of up to 690 g, was predicted to comply with UK Environmental Quality Standards, and potential risks associated with such treatments were deemed minimal. This allows a specific treatment plan to be chosen that is best suited for the welfare of the farmed fish, wild fish, and the wider environment.

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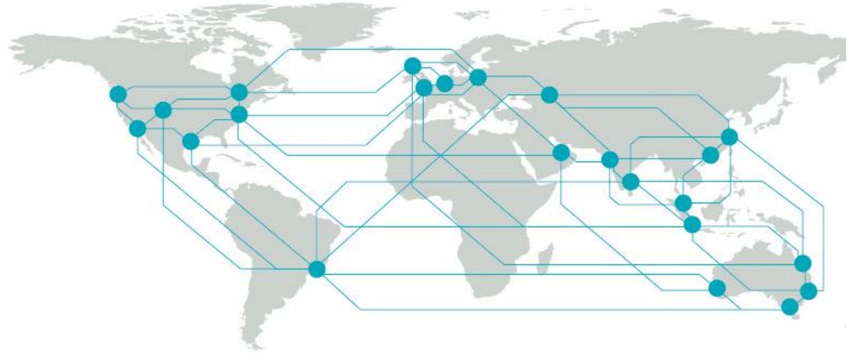

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