Ardgour (Linnhe)

Bath Medicine Dispersion Modelling Report

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EXECUTIVE SUMMARY

Dispersion model simulations have been performed to assess whether bath treatments at Ardgour (Linnhe) salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day, was simulated. Each pen with 120 metre circumference required 573 g of azamethiphos (the active ingredient in Salmosan, Salmosan Vet and Azasure) for treatment, resulting in a daily release of 573 g and a total discharge over 10 days of 5.73 kg. Simulations were performed separately for modelled neap and spring tides and a combined neap simulation, and the sensitivity of the results to key model parameters was tested.

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 573 g, should comply with the EQS. The peak concentration during the baseline simulation after 288 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 for Ardgour (Linnhe). The baseline simulation presented here was designed to be relatively conservative. Results are summarised in Table 1.

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:		Ardgour (Linnhe)	
Site location:		Loch Linnhe	
Peak biomass (T):		2,500	
CAGE DETAILS			
Number of pens:		10	
Cage dimensions:		120 m Circumference	
Working Depth (m):		15	
Cage group configuration:		2 x 5, 75 m matrix	
HYDROGRAPHIC SUMMARY		**ID277**	**ID282**
Surface Currents	**Ardgour (Linnhe)**	**May-Aug 2019**	**Aug-Sep 2019**
	Mean Speed (m/s)	0.111	0.117
	Residual Speed (m/s)	0.075	0.075
	Residual Direction (°G)	187.2	154.1
	Amplitude Parallel (m/s)	0.120	0.140
	Amplitude Normal (m/s)	0.086	0.095
	Major Axis (°G)	175	145
BATH TREATMENTS			
Recommended consent mass - 3hr Azamethiphos (g)		573	
Recommended consent mass - 24hr Azamethiphos (g)		573	

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 azamethiphos bath treatments on marine salmon farms near Ardgour, Loch Linnhe (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.

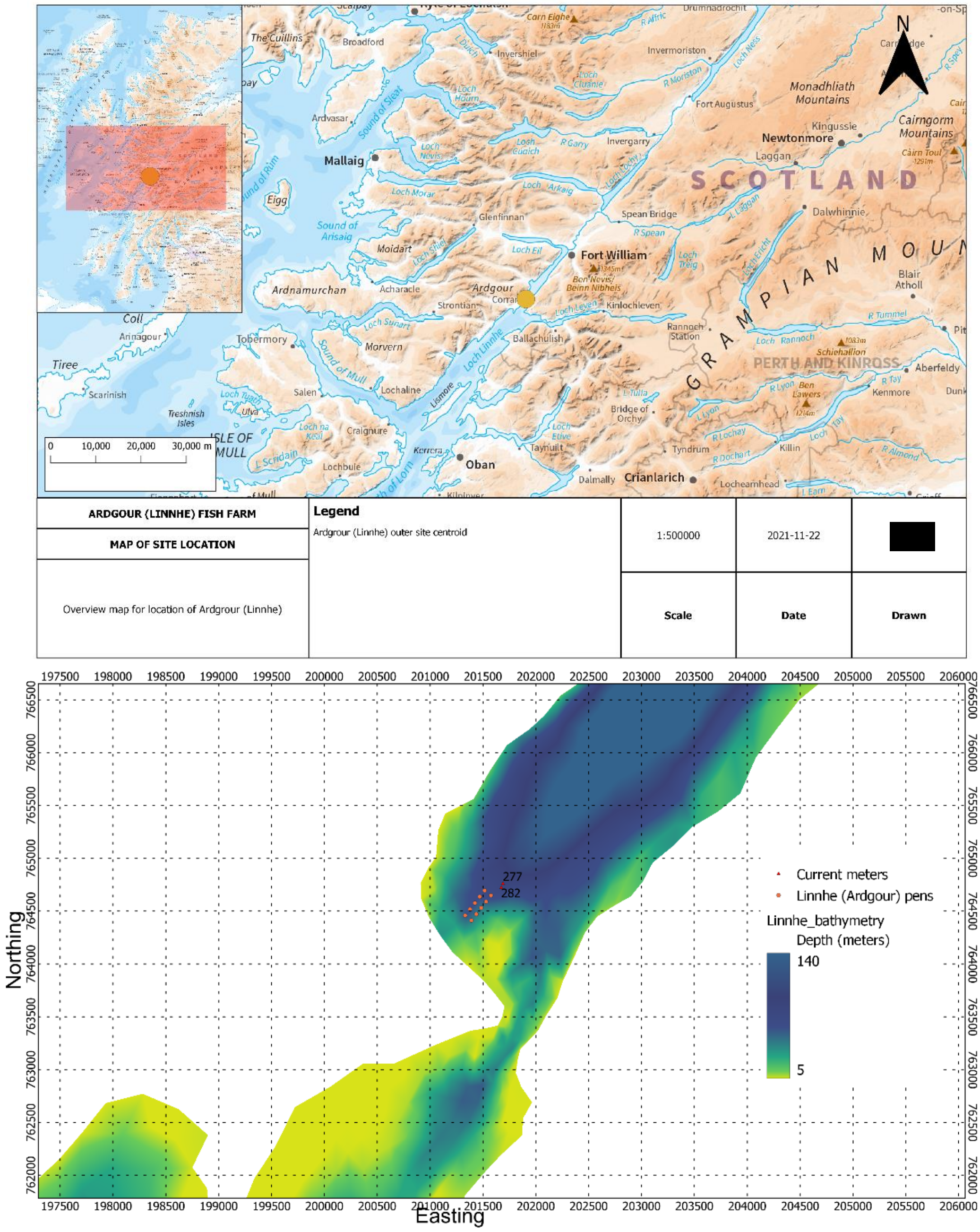

Figure 1. Location of Ardgour (Linnhe) salmon farm (top) and the location of the ADCP deployments in 2019 (▲) relative to the current pen positions (**o**).

The modelling procedure follows as far as possible guidance presented by SEPA in June 2019 (SEPA, 2019).

1.1 Site Details

The site is situated in Loch Linnhe NorthWest of the Corran Narrows, Loch Linnhe (Figure 1). Details of the sites are provided in Table 2, The receiving water is defined as a sea loch.

Table 2. Project Information

SITE DETAILS		
Site Name:	Ardgour (Linnhe)	
Site location:	Loch Linnhe	
Peak biomass (T):	2,500	
Proposed feed load (T/yr):	6387.5	
Proposed treatment use:	Azamethiphos	
CAGE DETAILS		
Group location:	NN01456455	
Number of cages:	10	
Cage dimensions:	120 m circumference	
Grid matrix (m)	75	
Working Depth (m):	16	
Cage group configuration:	2x5	
Cage group orientation (°G):	37.963	
Cage group distance to shore (km):	0.301	
Water depth at site (m):	38 – 45 m	
HYDROGRAPHIC DATA		
	ID277	ID282
Current meter position:	201688E 764762N	201672E 764724N
Depth at deployment position (m):	65.5	66.6
Duration of record (days):	85.125	30.76
Start of record:	23-May-2019	27-Aug-2019
End of record:	16-Aug-2019	27-Sep-2019
Current meter averaging interval (min):	20	20
Magnetic correction to grid North:	-2.71	-2.71

MODEL DETAILS

1.1 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 Annex A, and is only summarised here.

The hydrodynamic model used in this report was WeStCOMS version 2 (West Scotland Coastal Ocean Modelling System; Aleynik et al., 2016; Davidson et al., 2021), a hydrodynamic model implemented in FVCOM (Finite Volume Community Ocean Model) and coupled with WRF (Weather Research & Forecasting Model) version 2 becoming operational in April 2019. FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model developed by the University of Massachusetts School of Marine Science and the Woods Hole Oceanographic Institute (Chen et al., 2003). The model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure submodels. The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is presented using generalized terrain-following coordinates. The mathematical equations are discretized on an unstructured grid of triangular elements which permits greater resolution of complex coastlines, such as typically found in Scotland. Full details of the hydrodynamic modelling are described in Annex A.

For the particle tracking component, Mowi Scotland's in-house model UnPTRACK (Gillibrand, 2022) was used. This model has been used previously to simulate sea lice dispersal (Gillibrand & Willis, 2007), the development of a harmful algal bloom (Gillibrand et al., 2016) 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 cage 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 cage. The particles are then subject to advection, from the modelled flow fields, and horizontal and vertical diffusion. The choice of horizontal diffusion coefficient was informed by dye release experiments in the Southern Loch Linnhe area. After 72 hours, concentrations of medicine are calculated and compared with the relevant Environmental Quality Standard (EQS). Here, we have modelled the dispersion of azamethiphos following a treatment scenario to illustrate the quantities of medicine that disperse safely in the environment.

1.2 Model Domain and Boundary Conditions

The unstructured mesh used in the model was WeStCOMS2. The domain and mesh is shown in Figure 2, with the area around Ardgour (Linnhe) shown in Figure 3.

The mesh was not refined down to 25 m specifically in the area of the cages, since dispersion is not a localised process, unlike particulate deposition, and takes place over a much wider area. The mesh is relatively well resolved in the Ardgour area (Figure 3) and is completely adequate for modelling dispersion of solutes over spatial scales of 50 m to kilometres. The spatial resolution of the model varied from 50 m in some inshore waters to 3.5 km along the open boundary. In total, the model consisted of 99,999 nodes and 177,236 triangular elements.

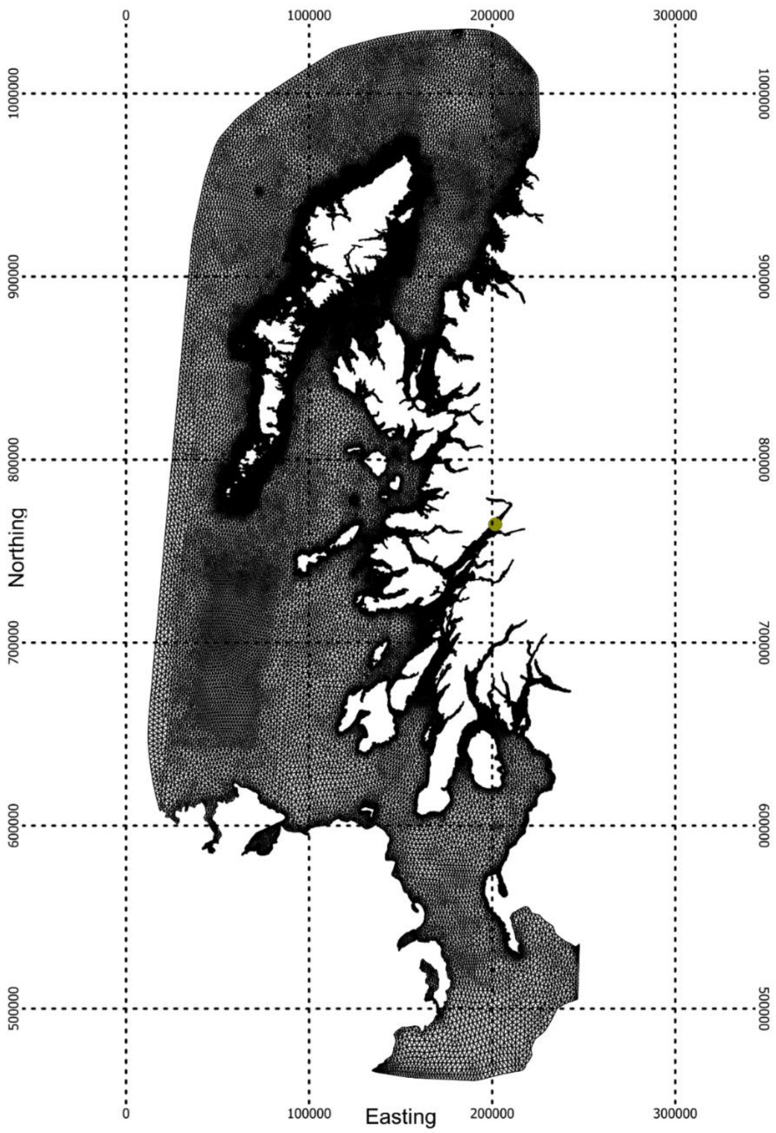

Figure 2. The WeStCOMS2 domain and mesh used in the Ardgour (Linnhe) modelling.

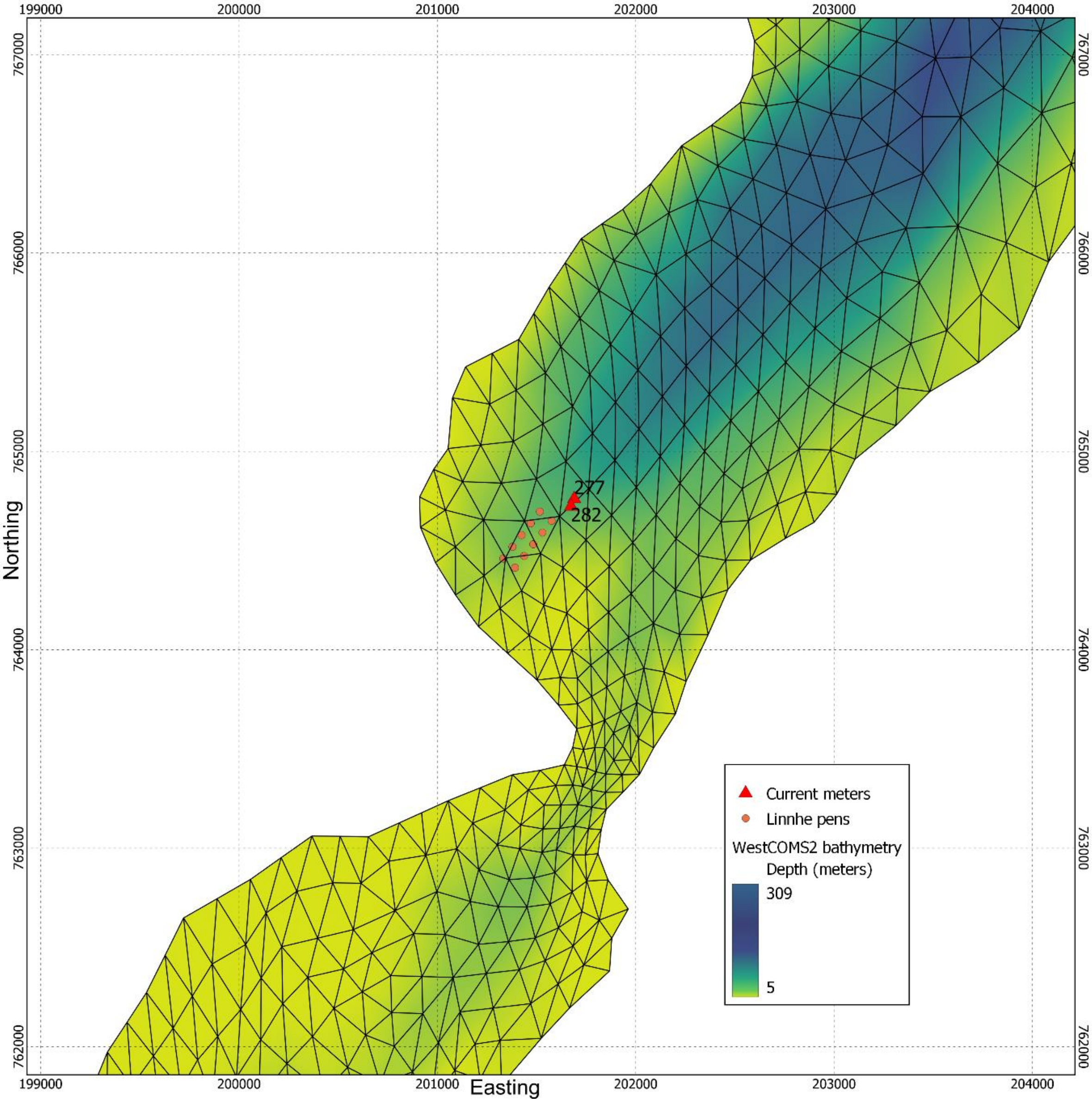

Figure 3. The model mesh in the area around the Ardgour (Linnhe) site with bathymetry. The pen locations (○) and current meter positions (▲) are indicated.

Bathymetry was taken from WeStCOMS2 model (Figure 4). Given that topical medicine dispersion occurs in the upper water column, it was not deemed necessary to use very detailed bathymetry data in the immediate vicinity to the cages.

WeStCOMS2 model's open lateral boundaries are forced with output from a relatively high resolution (2 km) North-East Atlantic ROMS operational model. Tides at the boundaries are derived from the Oregon State University inverse barotropic tidal solution. Fresh-water discharge and sea-surface forcing are supplied from a coupled regional Weather Research Forecasting (WRF v4, Aleynik et al., 2016). The WeStCOMS2 model is run with 10 equally-spaced sigma layers.

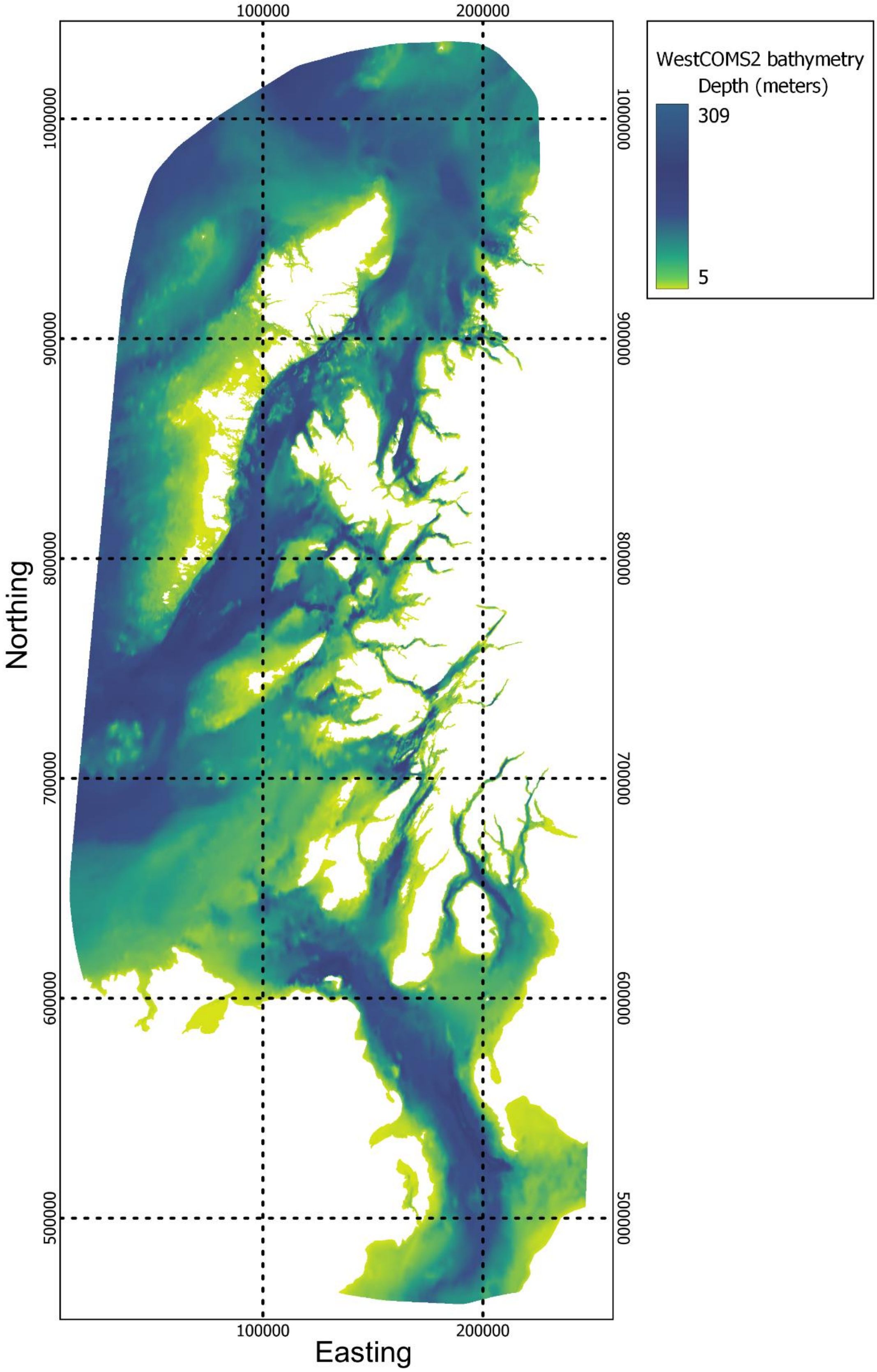

Figure 4. Bathymetry (meters), in the WeStCOMS2 domain.

1.3 Hydrodynamic Model Comparison

The hydrodynamic model was compared against current data and seabed pressure data, measured at Ardgour (Linnhe) using Acoustic Doppler Current Profilers (ADCP). Data are available at three locations (Figure 1) from:

(i) 23th May – 16th August 2019 (ID277)
(ii) 27th August – 29th September 2019 (ID282)

In total, the data extends over 115 days. Data was downloaded for the model for the same period as the observations and the modelled surface elevation and velocity at the two data locations were evaluated against the observed data. Details of the WeStCOMS2 model are given in Annex A.

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.

1.4 Medicine Dispersion Modelling

The medicine dispersion modelling, performed using the UnPTRACK model (Gillibrand, 2022), simulates the dispersion of patches of medicine discharged from cages following treatment using tarpaulins. The treatment scenario assumed one cage can be treated per day. This gives adequate time for installation of tarpaulins, dosage, and removal of tarpaulins for each cage.

To simulate the worst-case scenario, the dispersion modelling was initially conducted using flow fields over a period of 15 days centred on a small neap tidal range taken from the hydrodynamic model simulations. This is assumed to be the least dispersive set of ambient conditions, when medicine dispersion is least likely to meet the required EQS. Later simulations tested dispersion during spring tides.

A treatment depth of 5 m was chosen as a realistic net depth during application of the medicine for 120 m pens. The initial mass released per pen was calculated from the reduced cage volume and a treatment concentration of 100 µg/L, with a total mass of 5.73 kg of azamethiphos released during treatment of the farm. Particles were released from random positions within a cage radius of the centre and within the 0 – 5 m depth range. The simulations used *ca.* 954930 numerical particles in total, each particle representing 6 mg of Azamethiphos.

Each simulation ran for a total of 360 hours. This covered the treatment period (216 hours), a dispersion period to the EQS assessment after 288 hours (72 hours after the final treatment), and an extra 72 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.

From the calculated concentration fields, time series of two metrics were constructed for the whole simulation:
(i) The maximum concentration (µg/L) anywhere in the mesh;
(ii) The area (km^2) where the EQS was exceeded;

These results were used to assess whether the EQS (Environmental Quality Standard) or MAC (Maximum Allowable Concentration) 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 2019: ID277 (Figure 5) and ID282 (Figure 6).

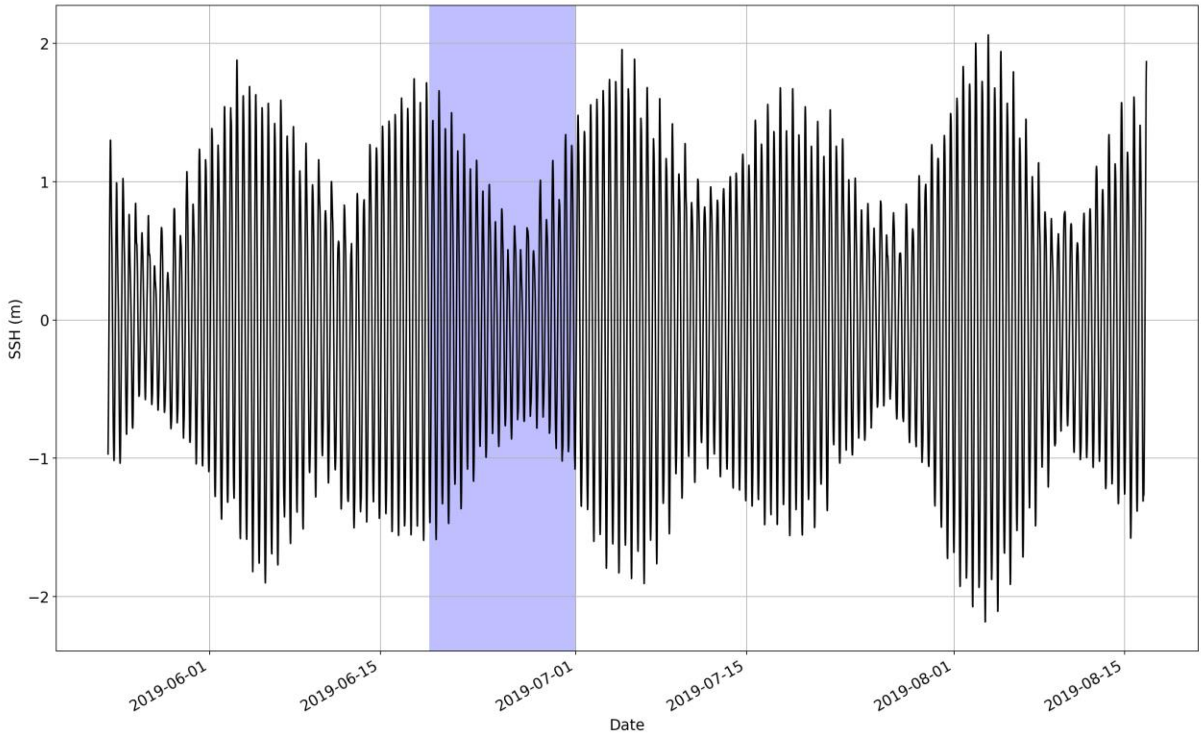

Figure 5. Sea surface height (SSH) at Ardgour (Linnhe) from 23th May – 16th Aug 2019 (ID277). Dispersion simulations were performed over period of neap tides (blue).

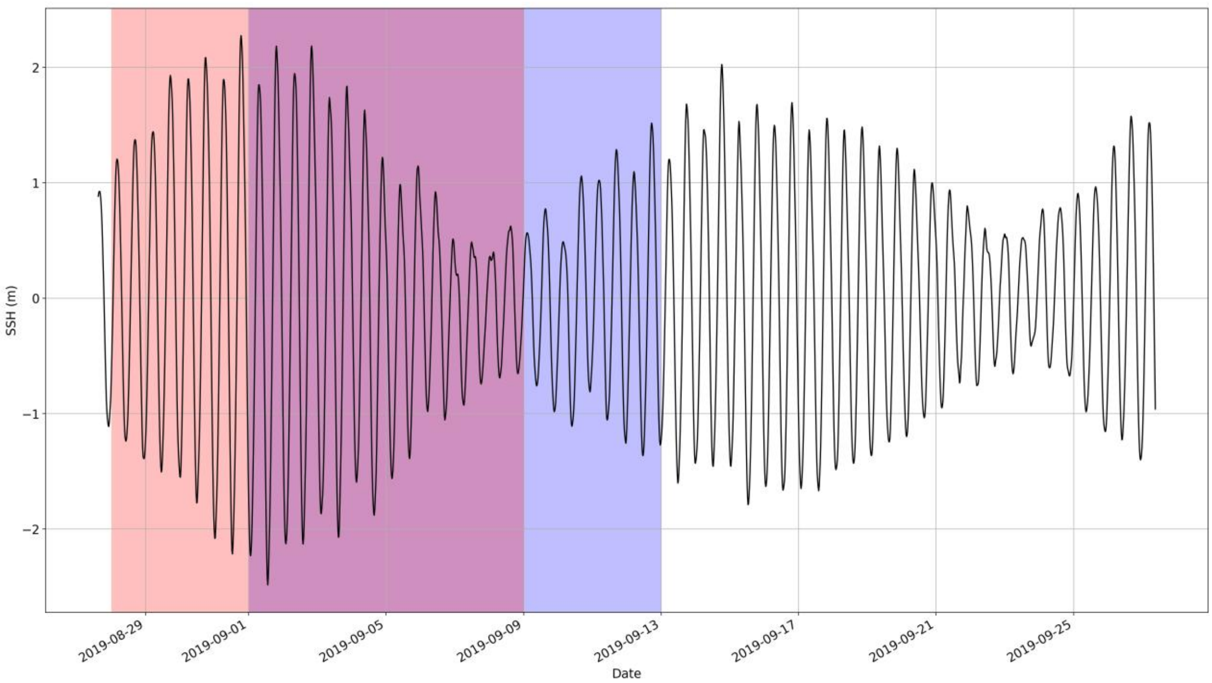

Figure 6. Sea surface height (SSH) at Ardgour (Linnhe) Outer from 27th August – 29th September 2019 (ID282). Dispersion simulations were performed over periods of spring tides (highlighted in red) and neap tides (blue).

1.5 Medicine Dispersion Simulations

The pen locations and details of the medicine source for Ardgour (Linnhe) 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.

Table 3. Details of the treatment simulated by the dispersion model for Ardgour (Linnhe). The release time is relative to the start of the neap or spring period highlighted in Figures 5 and 6.

Pen	Easting	Northing	Net Depth (m)	Treatment Mass (g)	Release Time (hr)
1	201517	764696	5	573	0
2	201391	764413	5	573	24
3	201332	764460	5	573	48
4	201437	764472	5	573	72
5	201378	764519	5	573	96
6	201483	764532	5	573	120
7	201424	764578	5	573	144
8	201530	764591	5	573	168
9	201470	764637	5	573	192
10	201576	764650	5	573	216

The simulations performed are listed in Table 4. All simulations used the release schedule and quantities outlined in Table 3. In Runs 9 – 14, the release schedule was set back by a number of hours to investigate the effect of tidal state at the time of release on the results. Results for these simulations are still presented in terms of time relative to the first release.

Table 4. Dispersion model simulation details for the treatment simulations of 10 pens at Linnhe.

Set	Run No.	$T_{1/2}$ (h)	K_H (m^2 s^{-1})	K_V (m^2 s^{-1})	Start Time
Neap Tides, Start Day = 29 (20th June 2019 – ID277)					
Baseline	1	134.4	0.1	0.001	00:00
1	2	213.6	0.1	0.001	00:00
	3	55.2	0.1	0.001	00:00
2	4	134.4	0.05	0.001	00:00
	5	134.4	0.2	0.001	00:00
3	6	134.4	0.1	0.0025	00:00
	7	134.4	0.1	0.005	00:00
	8	134.4	0.1	0.001	00:00 – 6 h
	9	134.4	0.1	0.001	00:00 – 4 h
4	10	134.4	0.1	0.001	00:00 – 2 h
	11	134.4	0.1	0.001	00:00 + 2 h
	12	134.4	0.1	0.001	00:00 + 4 h
	13	134.4	0.1	0.001	00:00 + 6 h
Spring Tides, Start Day = 1 (27th August 2019 – ID282)					
	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
5	17	134.4	0.05	0.001	00:00
	18	134.4	0.2	0.001	00:00
	19	134.4	0.1	0.0025	00:00
	20	134.4	0.1	0.0050	00:00
Neap Tides, Start Day = 6 (1st September 2019 – ID282)					
	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
6	24	134.4	0.05	0.001	00:00
	25	134.4	0.2	0.001	00:00
	26	134.4	0.1	0.0025	00:00
	27	134.4	0.1	0.0050	00:00

1.6 Diffusion Coefficients

Dale et al. (2020) described dye releases conducted South of Loch Linnhe in Ardmucknish Bay and Eilean Balnagowan. The report concluded that: ‘No observed concentrations imply a lateral diffusion coefficient of less than 0.1 m^2s^{-1}, so that value appears to be an appropriate conservative estimate for modelling the first hours following a treatment.’

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. 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.

Most of the simulations described here were conducted using a value of K_H = 0.1 m^2 s^{-1} which provided some conservatism in the results; however, the sensitivity of the model to K_H was explored.

3 RESULTS

3.1 Dispersion During Neap Tides, ID277

A standard treatment of 10 120 m pens, with a reduced net depth of 5 m and assuming one pen could be treated per day at a treatment concentration of 100 µg/L, resulted in a treatment mass per pen of Azamethiphos of 573 g for, a daily (24-h) release of 0.573 kg and a total treatment release of 5.73 kg over 216 hours. The dispersion of the medicine during and following treatment from Run No. 1 is illustrated in Figure 7. After 60 minutes, as the first days treatments was discharged, a discrete patch of medicine are evident. After 49 hours (2.042 days), as the last of the second days treatments was discharged, discrete patches of medicine from Day 2 are still evident, but the patches of medicine from the first day 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.

The treatment schedule completed after 216 hours (9 days). At this stage, the majority of the medicine released on earlier days has already dispersed Southwards in the prevailing flow of Loch Linnhe out past the Corran Narrows. 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 216 hours, the final treatment patches were rapidly dispersed and concentrations rapidly fell away.

The time series of maximum concentration from the simulation is shown in Figure 8. The 10 peaks in concentration of 100 µg/L following each treatment event over the first 10 days are evident. Following the final treatment after 216 hours, the maximum concentration fell steadily away (Figure 8). With a default half-life of 134.4 h (5.6 days), the maximum concentration seventy-two hours after the final treatment (time = 288 hours) was below 0.1 µg/L, the maximum allowable concentration (MAC). Twelve hours after the EQS time the maximum concentration rose briefly above the MAC.

The area where the EQS of 0.04 µg/L was exceeded peaked at about 0.96 km^2 after treatment on Day 8, but had fallen below 0.5 km^2 for the last time 20 hours before the final treatment; by 96 h after the final treatment, the exceeded area was zero (Figure 9).

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 achieved at 12 hours post EQS. In the following sections, the sensitivity of the model results to the medicine half-life, diffusion coefficients and tidal state are examined, with more realistic values being used in each case.

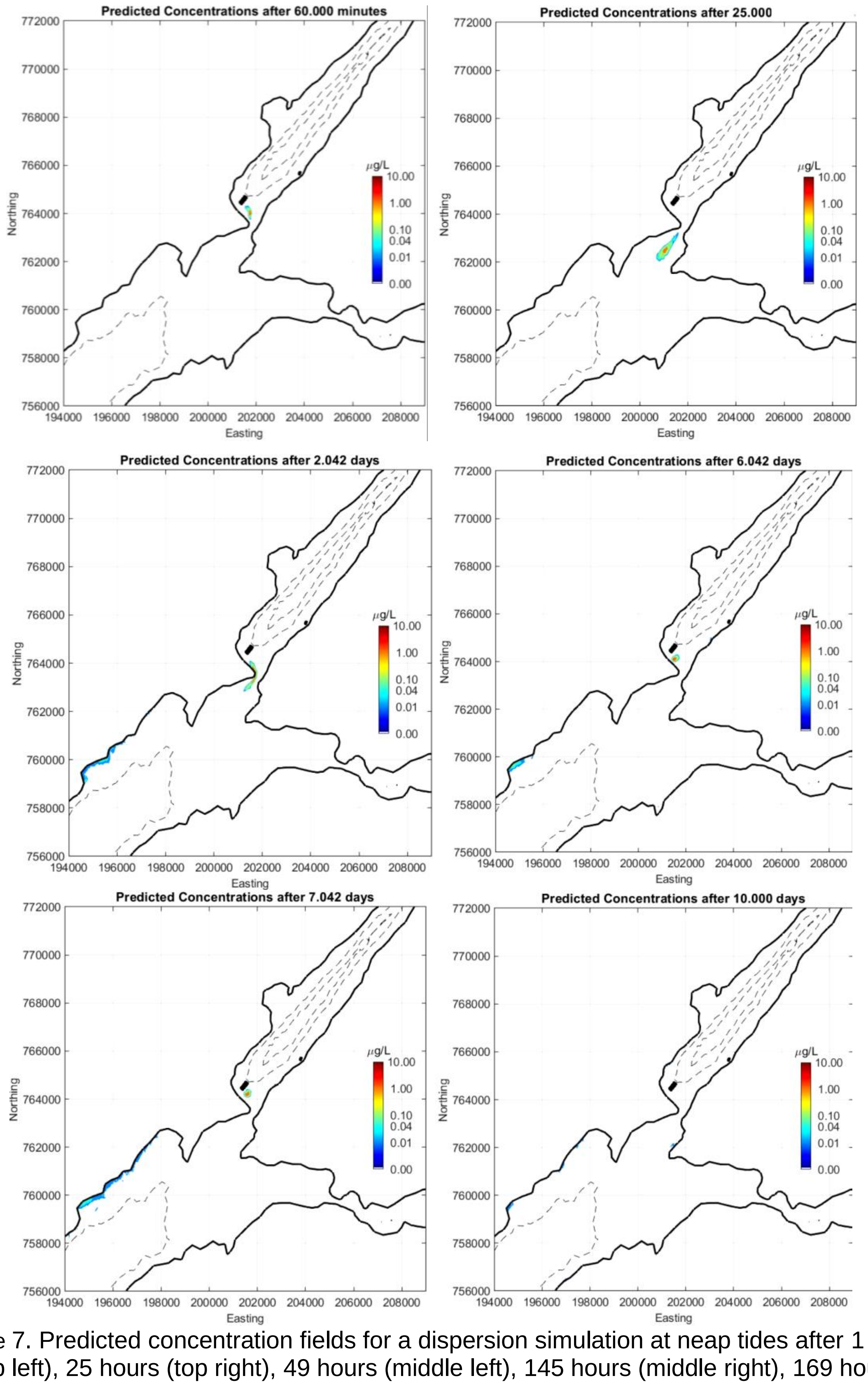

Figure 7. Predicted concentration fields for a dispersion simulation at neap tides after 1 hour (top left), 25 hours (top right), 49 hours (middle left), 145 hours (middle right), 169 hours (bottom left) and 240 hours (bottom right).

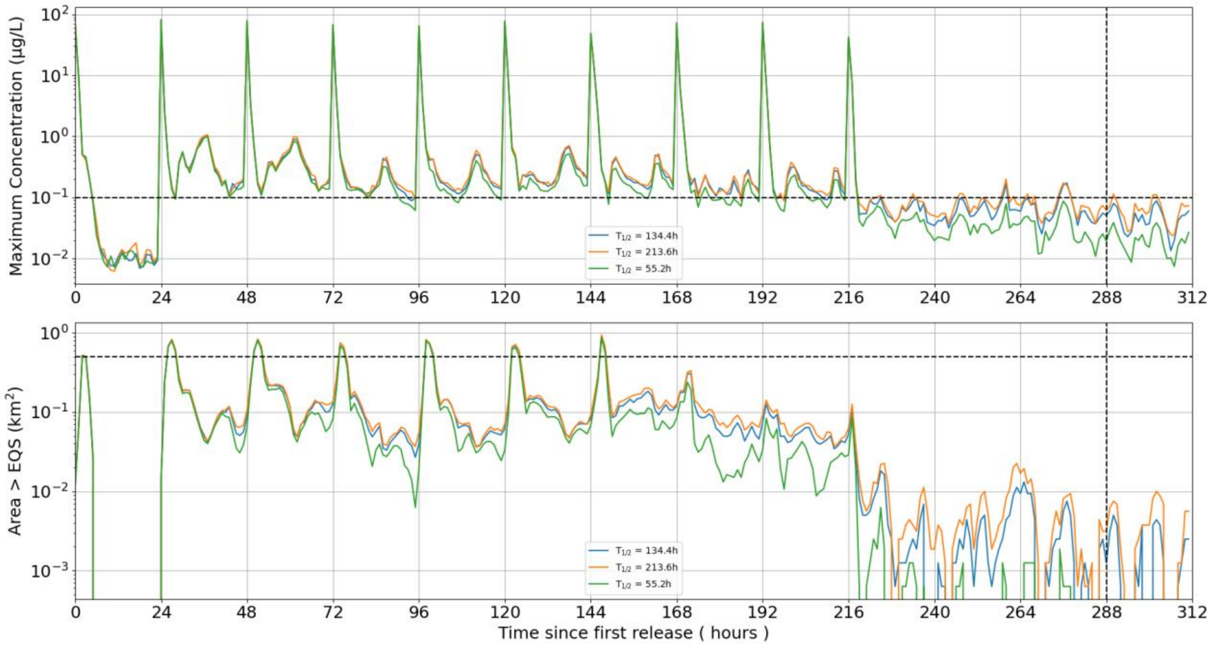

Figure 8. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the first set of model runs (Table 4). The model was run during neap tide with varying medicine half-life ($T_{1/2}$). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.2 Sensitivity to Half-Life

The half-life of 134.4 h (5.6 days) is thought to be conservative. The EQS was achieved, and was passed with half-lives of 134.4h and 55.2h (Figure 8). The area where the EQS of 0.1 µg/L is exceeded peaked at about 0.99 km^2 and 0.8775 km^2 between treatments on Days 7 and 8, but had fallen well below 0.5 km^2, for all simulated half-lives, 20 hours prior to the final treatment (Figure 8). 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 diffusion coefficient used was derived from the model, the diffusion coefficients estimated from through dye patches near Ardgour (Linnhe) had a mean value below 0.1 m^2 s^{-1}. Simulations were therefore performed with lower and higher values of K_H, specifically K_H = 0.05 m^2 s^{-1} and K_H = 0.2 m^2 s^{-1} (Figure 9).

The time series of maximum concentration and area exceeding the EQS are shown in Figure 9. The time series confirm that the MAC wasn't exceeded after 288 hours (72 hours after the final treatment).

Similarly, sensitivity to the vertical diffusion coefficient, K_V, was tested (Figure 10). The model is not particularly sensitive to the vertical diffusion rate, but increased vertical diffusion, likely in the presence of wind and/or waves, led to slightly lower peak concentrations and a smaller area where the EQS was exceeded.

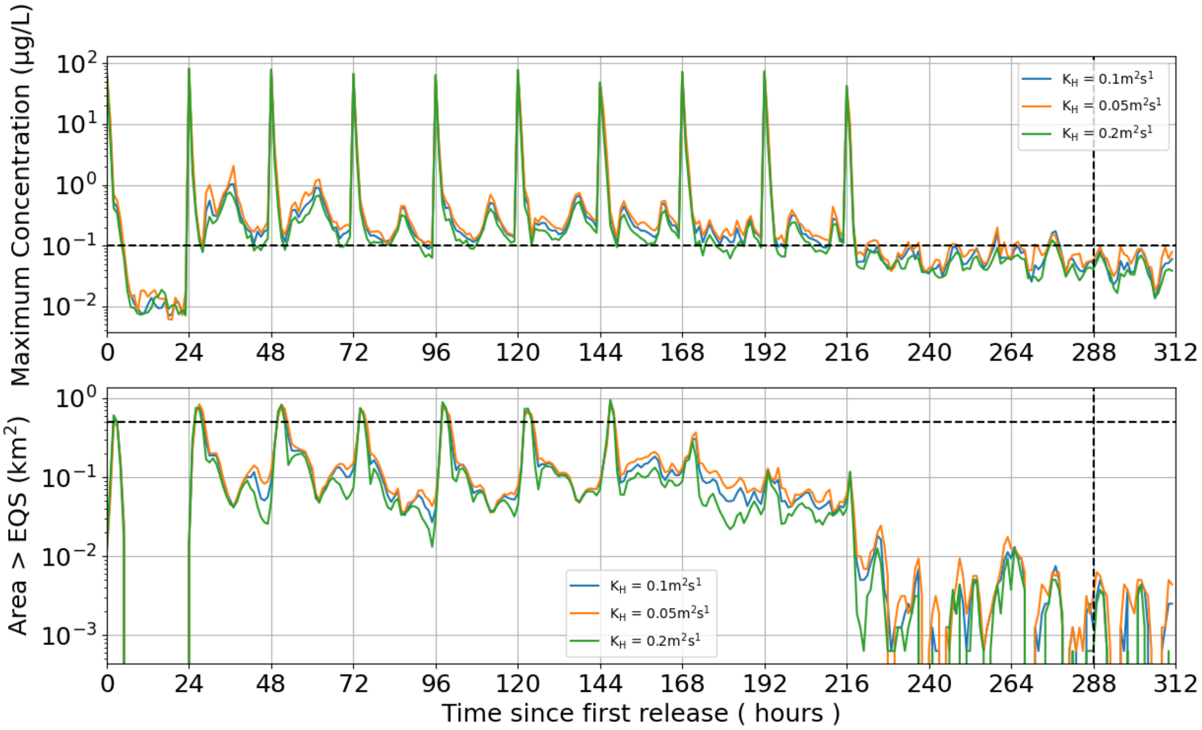

Figure 9. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the second set of model runs (Table 4). The model was run during neap tide with varying horizontal diffusion coefficient K_H. The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

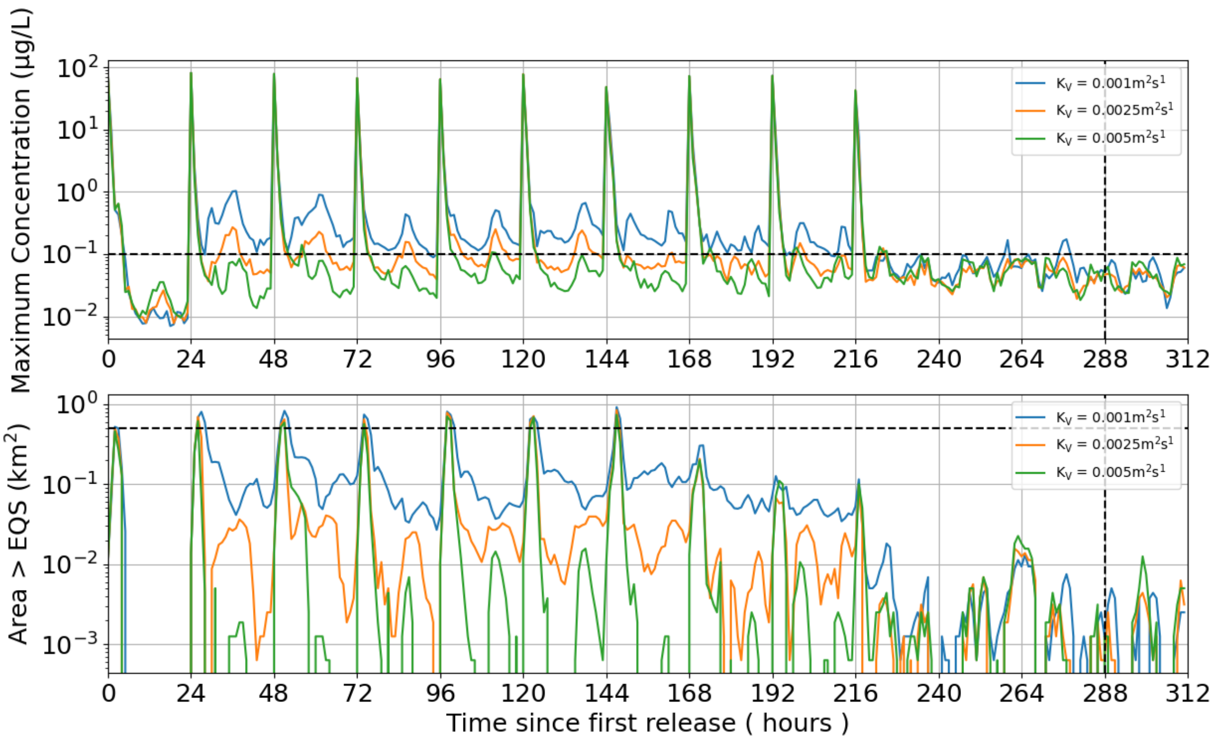

Figure 10. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the third set of model runs (Table 4). The model was run during neap tides with varying vertical diffusion coefficient K_V. The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km² are indicated by the horizontal dashed lines.

3.4 Sensitivity to Release Time

The baseline simulations were 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 a little variability (Figure 11), all results are below MAC at EQS time with several results marginally exceeding the MAC post EQS time. However, in no case was the MAC exceeded after 308 hours, it should be noted that a relatively conservative half-life of 5.6 days is being used here.

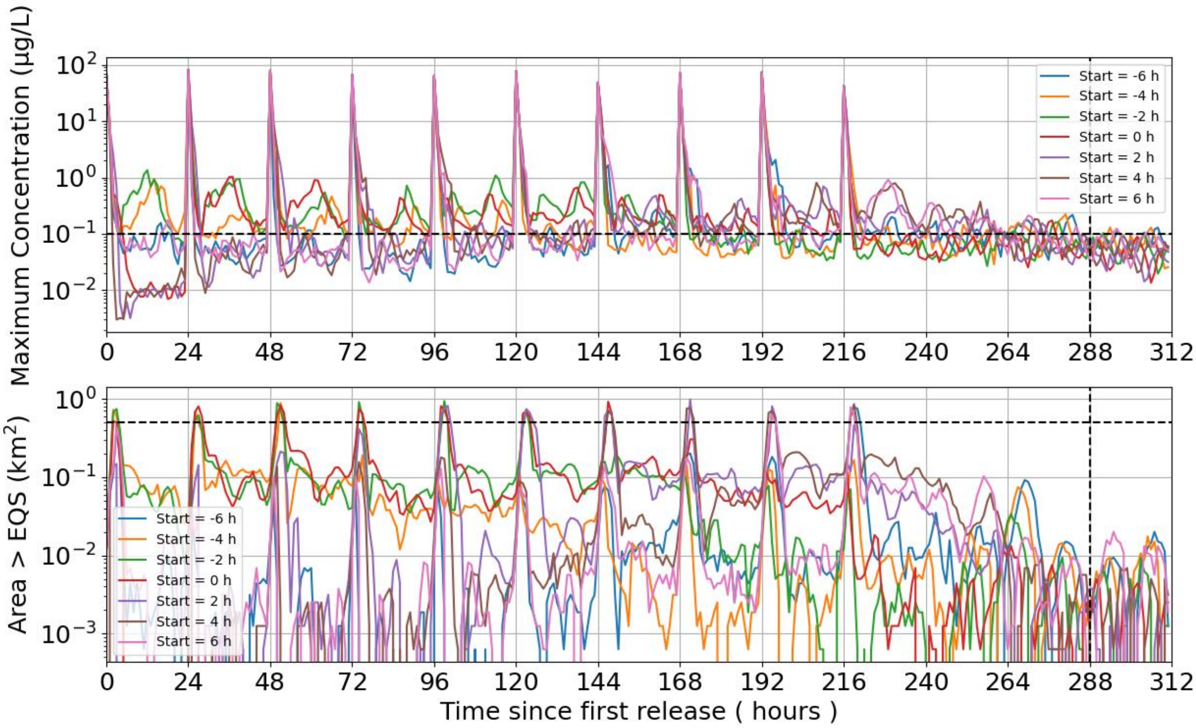

Figure 11. Time series of maximum concentration (top) and area exceeding the EQS (bottom) from the fourth set of model runs (Table 4). The model was run during neap tides with varying release times, relative to the baseline (Start = 0 h). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.5 Dispersion during Spring Tides, ID282

Dispersion simulations were carried out during modelled spring tides in August - September 2019 (Figure 7), 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 573 g of azamethiphos. The MAC and area EQS were achieved comfortably for all variations. Dispersion at spring tides is greater than at the small tidal range during the neap tide simulated in June - July 2019.

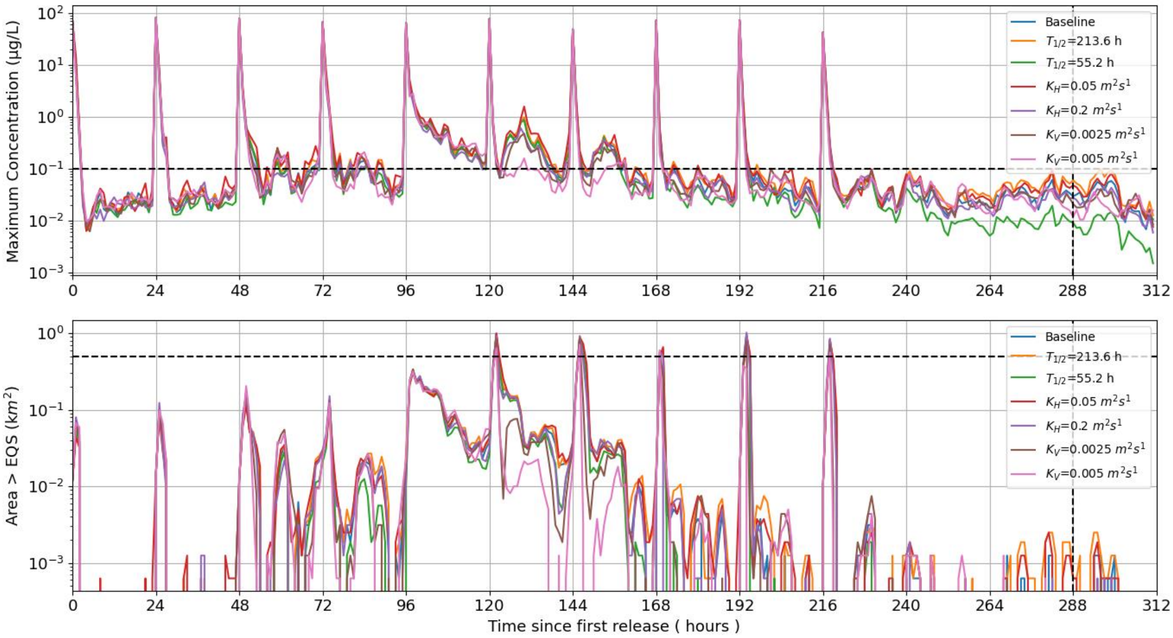

Figure 12. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the fifth set of model runs (Table 4). The model was run at spring tides with varying medicine half-life ($T_{1/2}$), horizontal diffusion coefficient (K_H) and vertical diffusion coefficient (K_V). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

Given the comfortable compliance with the MAC and EQS at spring tides, simulations investigating the effects of release times were not performed.

3.6 Dispersion During Neap Tides, ID282

A further set of dispersion simulations during modelled neap tides from 1st September – 15th September 2019 (Table 4), 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 573 g of azamethiphos. For all medicine half-lives, and horizontal and vertical diffusion coefficients simulated, both the MAC and area EQS were comfortably achieved aside from the conservative half-live of 213.6 h and horizontal diffusivity of 0.05 m^2 s^{-1} (Figure 13). These simulations demonstrate again that the modelled treatment regime will meet the EQS criteria.

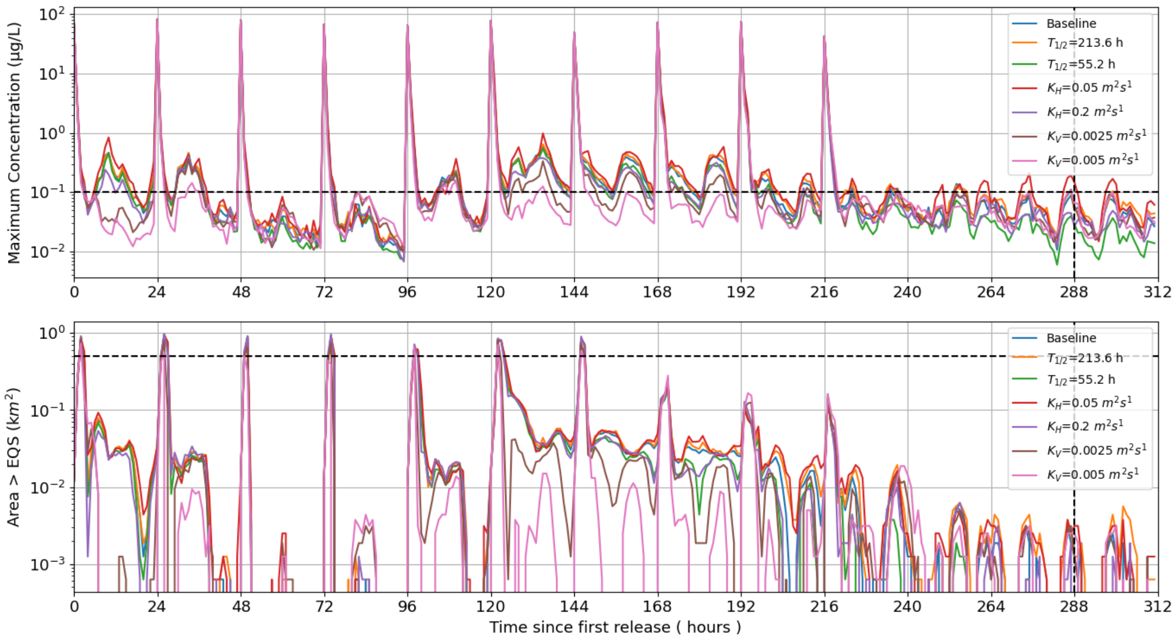

Figure 13. Time series of maximum concentration (top) and the area where concentrations exceeded the EQS (bottom) from the sixth set of model runs (Table 4). The model was run at neap tides in September 2016 with varying medicine half-life ($T_{1/2}$), horizontal diffusion coefficient (K_H) and vertical diffusion coefficient (K_V). The MAC and area limit 72 hours after the final treatment (Time = 216 h) of 0.1 µg/L and 0.5 km^2 are indicated by the horizontal dashed lines.

3.7 3-Hour EQS

The time series of the area where the 3-hour EQS of 250 ng L^{-1} was exceeded for each individual pen treatment at neap tide (first release on 19th June 2019) are shown in Figure 14. For each treatment, the area exceeding the EQS was less than the allowable mixing zone (0.17 km^2) after 3 hours. The peak concentration of 100 µg L^{-1} fell to less than 10 µg L^{-1} within the 3-hour period.

For spring tide releases (first release on 22th July 2020), the area where concentrations exceeded the 3-hour EQS also complied with the allowable area (Figure 15). Similarly to the neap tide simulation, the peak concentrations fell by an order of magnitude within the three hours.

This demonstrates that the discharge of Azamethiphos from the Ardgour (Linnhe) site should not breach the 3-hour Environmental Quality Standard.

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 (m s^{-1})	0.111
Area of a 120 m circumference pen (m^2)	1145.92
Distance from shore (km)	336
Mean water depth (m)	30
Treatment Depth (m)	5
Mixing Zone Ellipse Area (m^2)	175,034.43

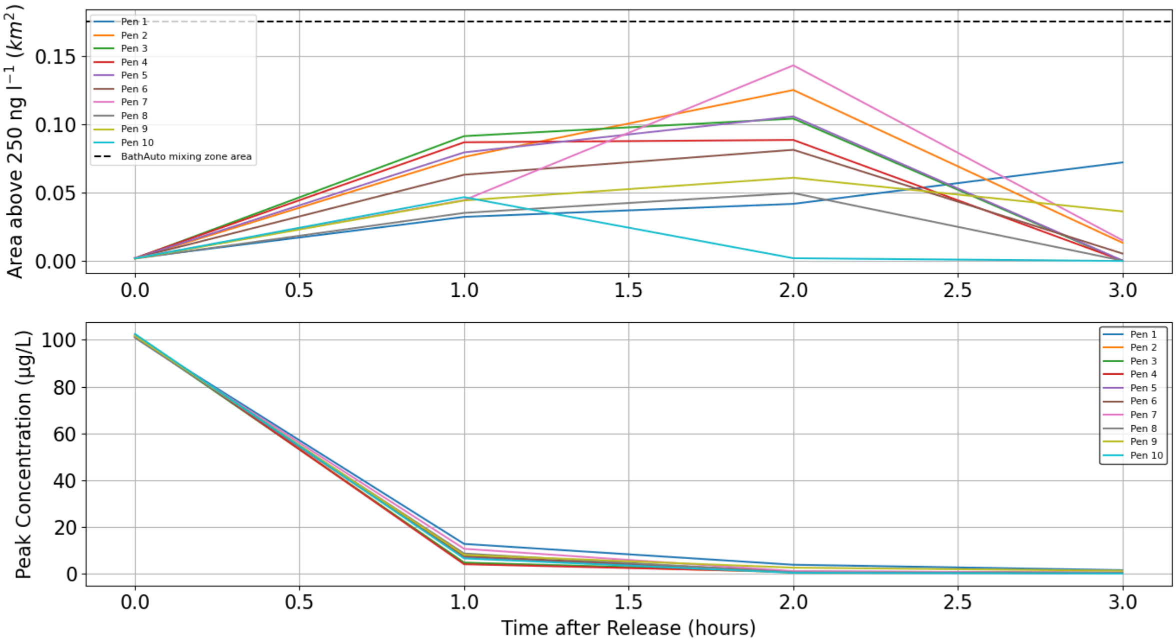

Figure 14. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at neap tide. The 3-hour mixing zone area is indicated (---).

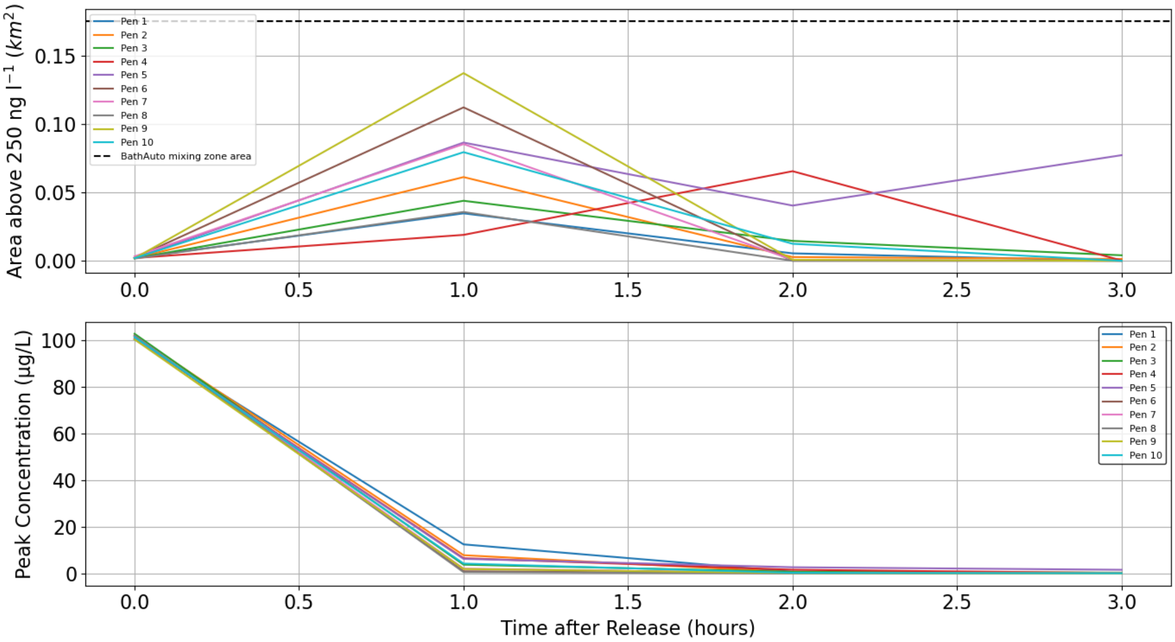

Figure 15. Time series of the area exceeding the 3-hour EQS (top) and the peak concentration (bottom) for each individual pen treatment during the 3 hours following release at spring tide. The 3-hour mixing zone area is indicated (---).

3.8 Sensitive Features

Two sensitive features have been identified to the Northeast of Ardgour (Linnhe) at a distance of approximately 2.6 km. Time series of concentrations at the locations of the sensitive features are presented in Figure 19 for the near bed (5 m) section of the water column. The concentrations at the sensitive features are three orders of magnitude less than the MAC for Azamethiphos (100 ng/L).

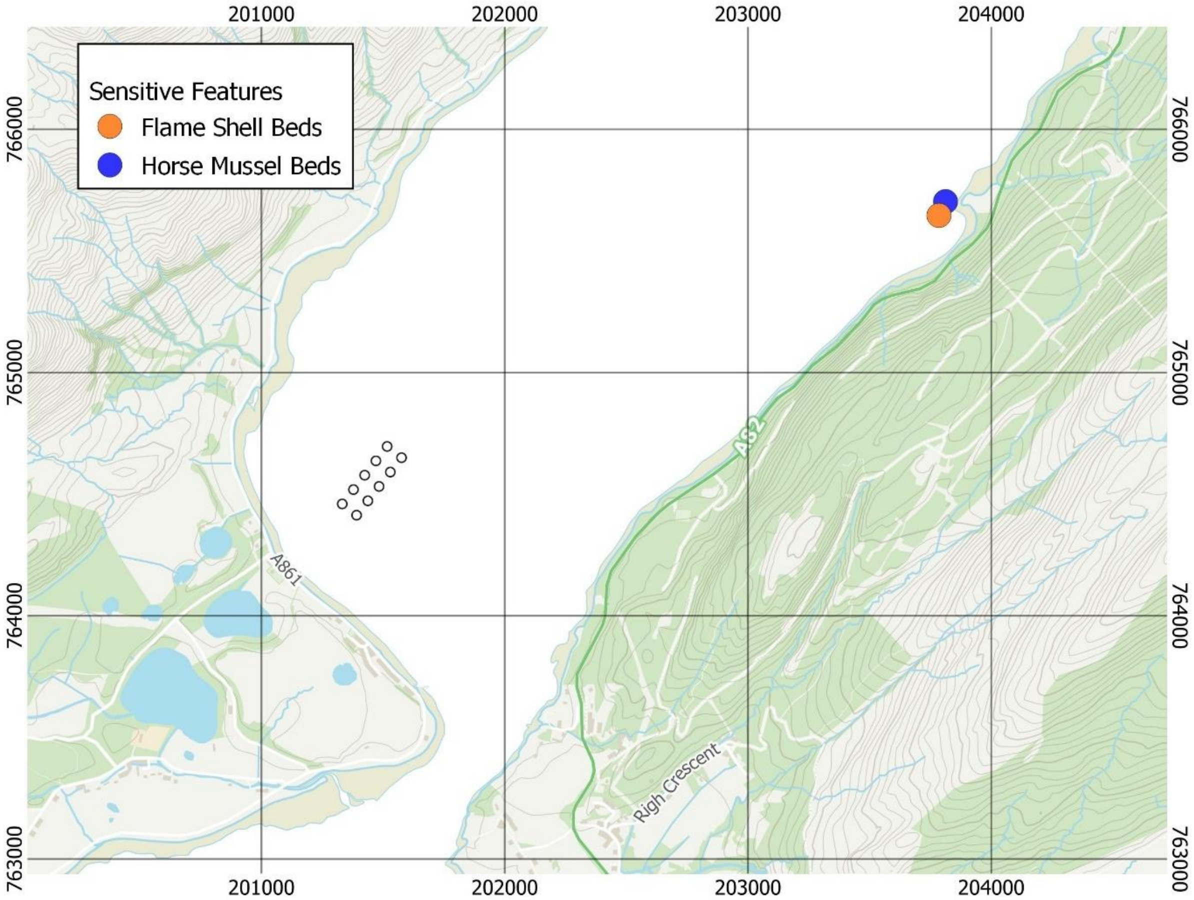

Figure 16. Sensitive Features identified

Table 6. Sensitive Features

PRIORTIY MARINE FEATURE	Easting	Northing
Horse Mussel Beds	203812	765703
Flame Shell Beds	203785	765646

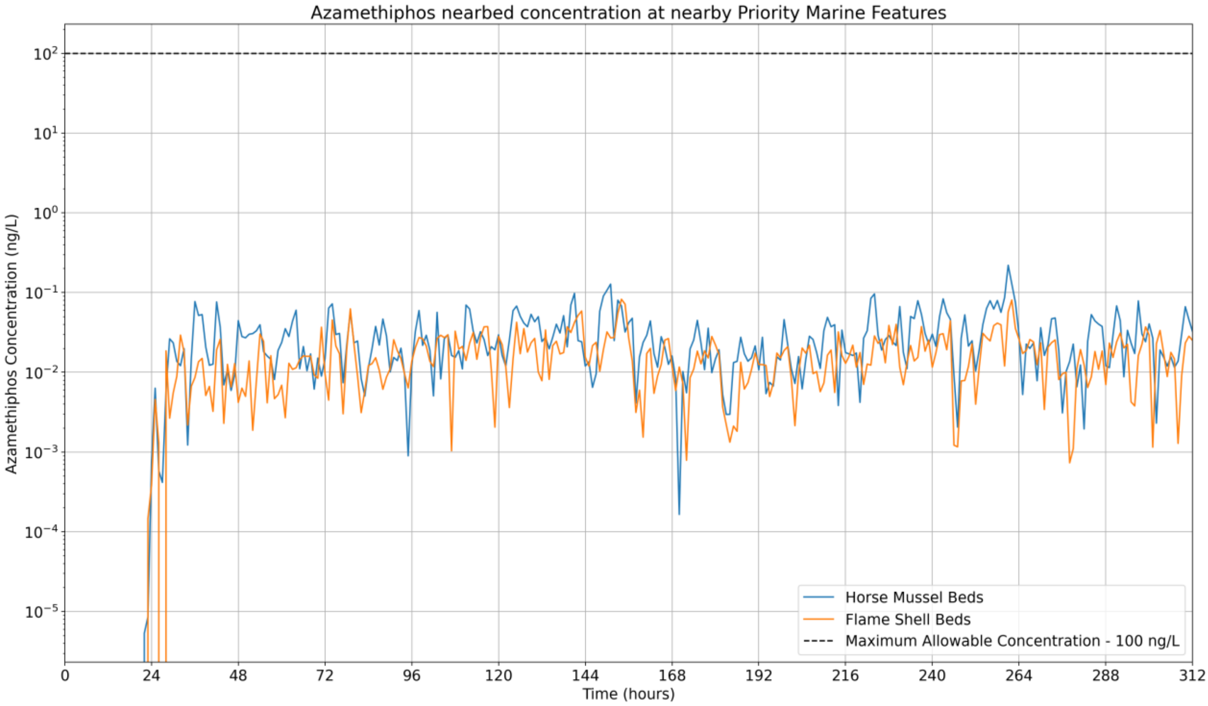

Figure 17. Time series of Azamethiphos concentration (ng/L) in the bottom 5 meters of the water column during a neap tide (Run 01) at the location of the Sensitive Feature identified.

4 SUMMARY AND CONCLUSIONS

A total of 27 dispersion simulations have been performed to assess whether bath treatments at Ardgour (Linnhe) salmon farm will comply with pertinent environmental quality standards. A realistic treatment regime, with 1 pen treatment a day, was simulated. Each pen at Ardgour (Linnhe) required 573 g of azamethiphos for treatment, resulting in a daily release of 0.573 kg and a total discharge over 10 days of 5.73 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 7.

Table 7.Summary of Results

SITE DETAILS			
Site Name: Site location: Peak biomass (T):		Ardgour (Linnhe) Loch Linnhe 2,500	
CAGE DETAILS			
Number of cages: Cage dimensions: Working Depth (m): Cage group configuration:		10 120 m Circumference 15 2 x 5, 75 m matrix	
HYDROGRAPHIC SUMMARY		**ID277**	**ID282**
Surface Currents	**Linnhe**	**May-Aug 2019**	**Aug-Sep 2019**
	Mean Speed (m/s)	0.111	0.117
	Residual Speed (m/s)	0.075	0.075
	Residual Direction (°G)	187.2	154.1
	Tidal Amplitude Parallel (m/s)	0.120	0.140
	Tidal Amplitude Normal (m/s)	0.086	0.095
	Major Axis (°G)	175	145
BATH TREATMENTS			
Recommended consent mass – 3h Azamethiphos (g)		573	
Recommended consent mass - 24h Azamethiphos (g)		573	

The model results confirmed that the treatment scenario proposed, with a daily release of no more than 0.573 kg, should consistently comply with the EQS. The peak concentration during the baseline simulation after 289 hours (73 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 most simulations performed, including some sensitivity testing, the EQS criteria were met. Simulations over two different neap tides from 2019 demonstrated that the modelled treatment regime consistently complied with the relevant EQS. For the simulation during spring tides, greater dispersion meant that the EQS were met very comfortably. Therefore, we believe that the requested daily quantity of 0.573 kg of azamethiphos can be safely discharged without breaching the 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 7.

5 REFERENCES

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ANNEX A. HYRODYNAMIC MODEL DESCRIPTION

A.1 Model Description

The hydrodynamic model used in this report was WeStCOMS version 2 (West Scotland Coastal Ocean Modelling System) a hydrodynamic model implemented in FVCOM (Finite Volume Community Ocean Model) and coupled with WRF (Weather Research & Forecasting Model) developed by Dr. Dmitry Aleynik at the Scottish Association for Marine Science (SAMS), version 2 becoming operational in April 2019.

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

The mathematical equations are discretized on an unstructured grid of triangular elements which permits greater resolution of complex coastlines, such as typically found in Scotland.

A.2 Configuration and Boundary Forcing for WeStCOMS version 2

WeStCOMS version 2 open lateral boundaries are forced with output from a relatively high resolution (2 km) North-East Atlantic ROMS operational model, provided by the Marine Institute, Ireland. Fresh-water discharge and sea-surface forcing are supplied from a coupled high resolution regional Weather Research Forecasting (WRF v4) model run simultaneously.

The diffusion characteristics of WeStCOMS version 2 model have been validated using dye studies performed in October 2019 in Loch Linnhe, dye was released into surface waters near the eastern shore. (Dale et al. 2020)

The unstructured mesh used was WestCOMS version 2. The domain and mesh is shown in Figure 2, with the area around Ardgour (Linnhe) shown in Figure 3.

The mesh was not refined down to 25 m specifically in the area of the cages, since dispersion is not a localised process, unlike particulate deposition, and takes place over a much wider area. However, the mesh, is relatively well resolved in the Loch Linnhe area (Figure 3) and is completely adequate for modelling dispersion of solutes. The spatial resolution of the model varied from 50 m in some inshore waters to 3.5 km along the open boundary. In total, the model consisted of 99,999 nodes and 177,236 triangular elements.

A.3 WeStCOMS version 2 - ADCP comparison

For the current study, the model was compared against hydrographic data collected in the region of the farm site in 2019. The data are described in the relevant hydrographic reports. In March 2019, an Acoustic Doppler Current Profiler (ADCP) was deployed close to the Ardgour (Linnhe) farm site until August 2019. A further deployment was made from August – September 2019. In all, over 115 days of current data were used in this application. ADCP deployments provided both current velocity and seabed pressure data, which were used to calibrate and validate modelled velocity and sea surface height. The WeStCOMS version 2 model was compared initially against data from 23rd May – 16th August 2019 and then against the data from both 27th August – 27th September 2019.

The following ADCP deployments were compared with the WeStCOMS version 2 hydrodynamic flows:

1. May – August 2019 (ADCP deployment ID277)
2. August – September 2019 (ADCP deployment ID282)

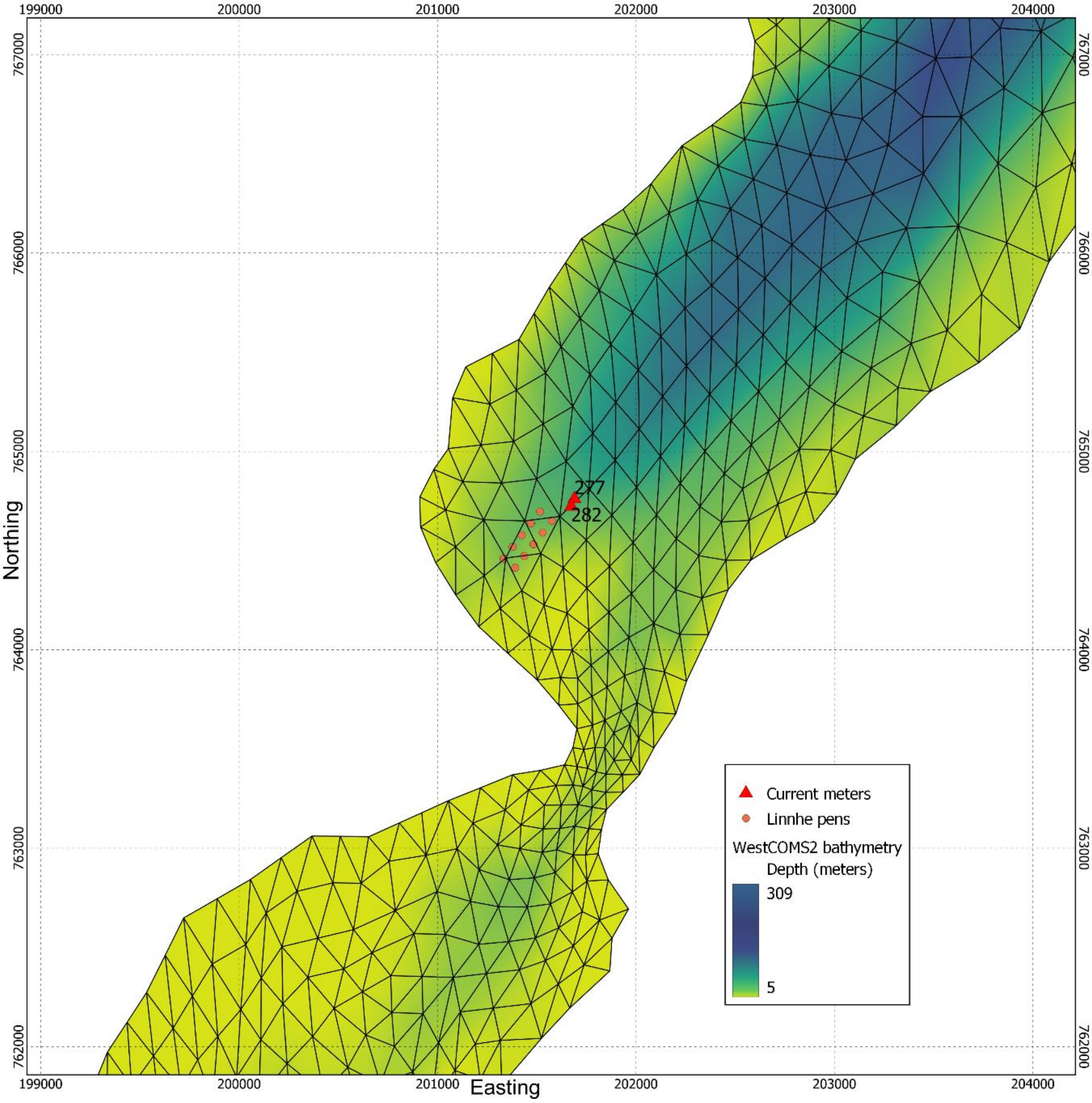


Figure A.1. Locations of the ADCP deployments relative to the 10 pens at the site.

Model performance is assessed using three metrics: the mean absolute error (MAE), the root-mean-square error (RMSE) and the model skill (d_2). The first two are standard measures of model accuracy; the third, d_2, is taken from Willmott et al. (1985) and lies in the range $0 \leq d_2 \leq 1$, with $d_2 = 0$ implying zero model skill and $d_2 = 1$ indicating perfect skill.

A.3.1 May – August 2019

Observed pressure and current velocity from the ADCP location was compared with modelled sea surface height (SSH) and velocity (ADCP deployment ID277).

The results of the comparison exercise are presented in Figures A.2 – A.5 and Table A.A.2. At the ADCP location, the sea surface height was reasonably accurately modelled, with model skill of 0.99. The mean absolute error (MAE) and root-mean-square error (RMSE) values of 0.13 m and 0.16 m respectively are about 3.1% and 3.8% of the spring tide range respectively.

North and east components of velocity at the ADCP location were satisfactorily reproduced by the model, with values of the model skill, d_2, of 0.47 and 0.48 at 8.6 m and 18.6 m depth for East velocities and 0.66 for both depths for North velocities (Figure A.3, Table A.2). The model slightly underpredicted the magnitude of the strongest observed currents (Figures A.4 and A.5), with values of MAE and RMSE being in the range 4 – 7 cm s^{-1} (Table A.3). This underprediction is unsurprising, with the model showing more spatially-smoothed currents than occur in reality, and provides a degree of conservatism in the following dispersion modelling. The scatter plots and histograms shown in Figures A.4 and A.5 demonstrate that the modelled currents were broadly of the same speed and direction as the observed data.

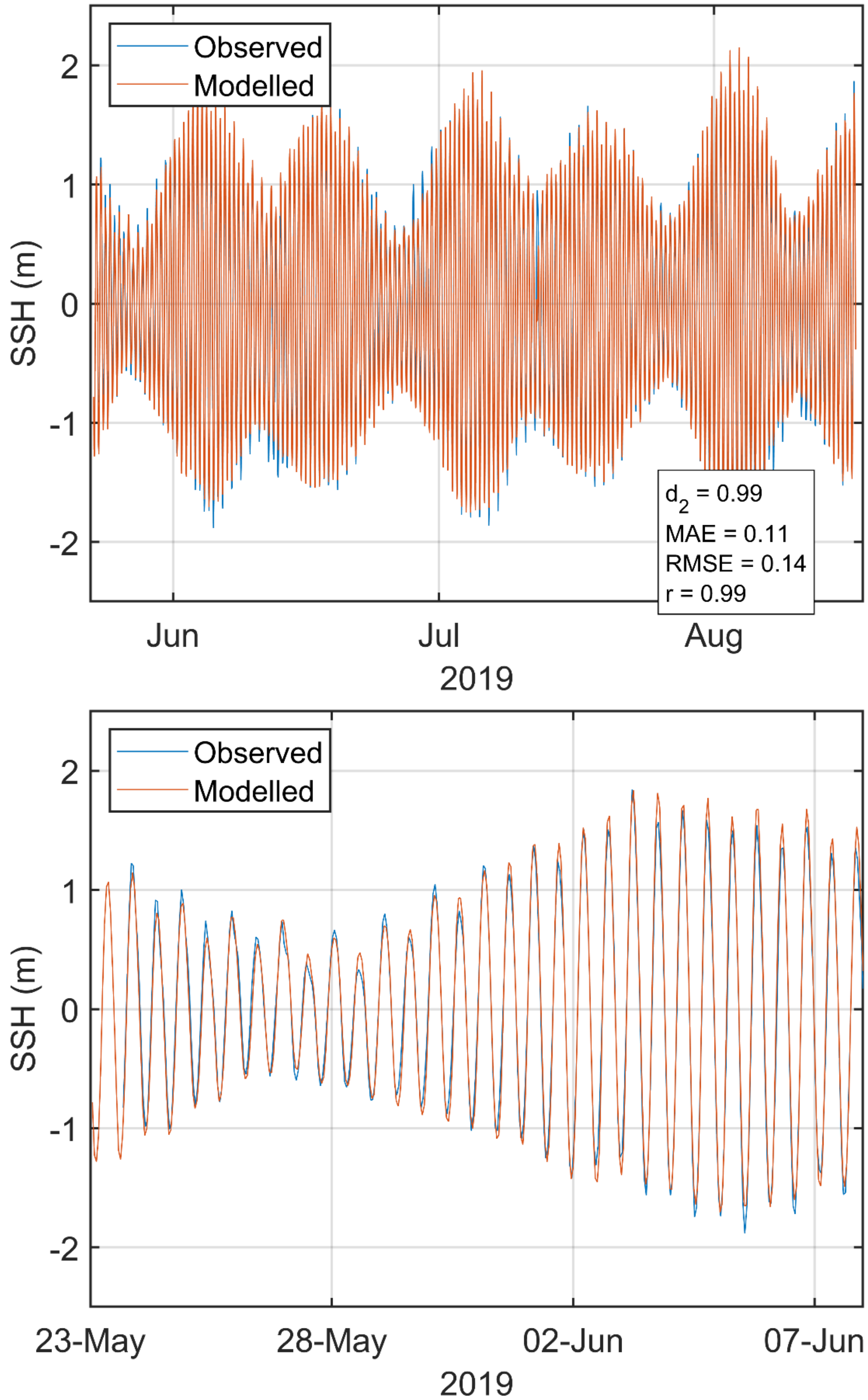


Figure A.2. Comparison between observed and modelled sea surface height from May - August 2019 (ADCP deployment ID277). Both the full record (top) and a subset of 15 days (bottom) are shown. Observed data are in blue, model results in red.

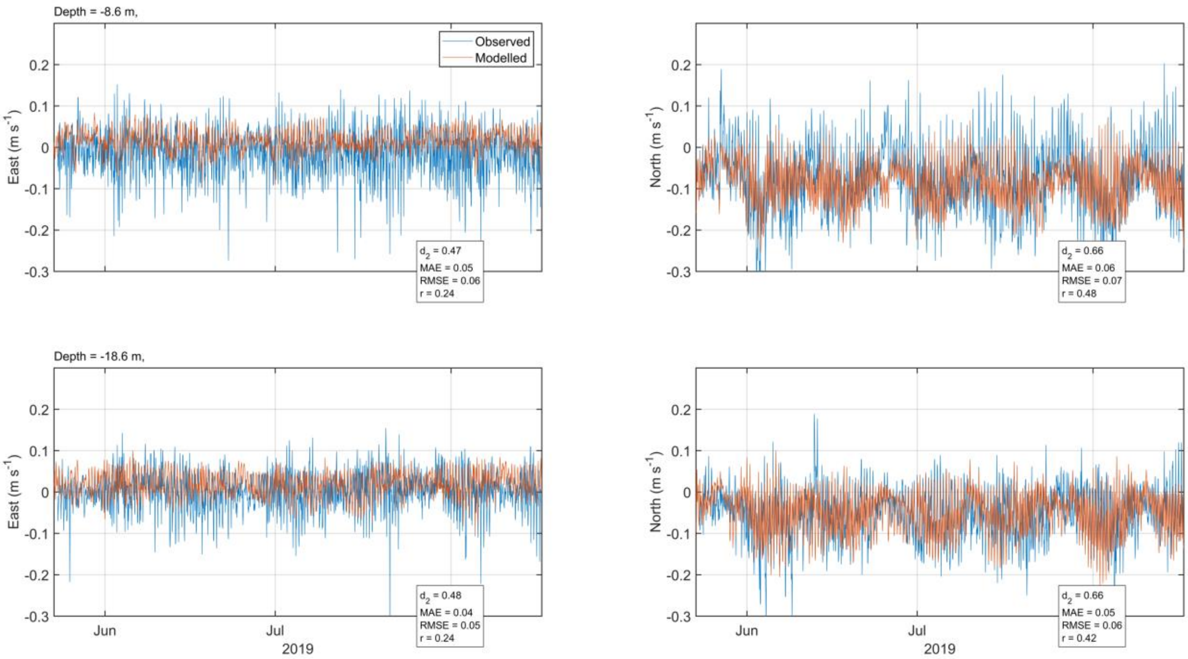


Figure A.3**.** Comparison between observed and modelled East (left) and North (right) components of velocity at the ADCP location for two depths 8.6m (top) and 18.6m (bottom) for 15 days in May – August 2019. Observed data are in blue, model results in red.

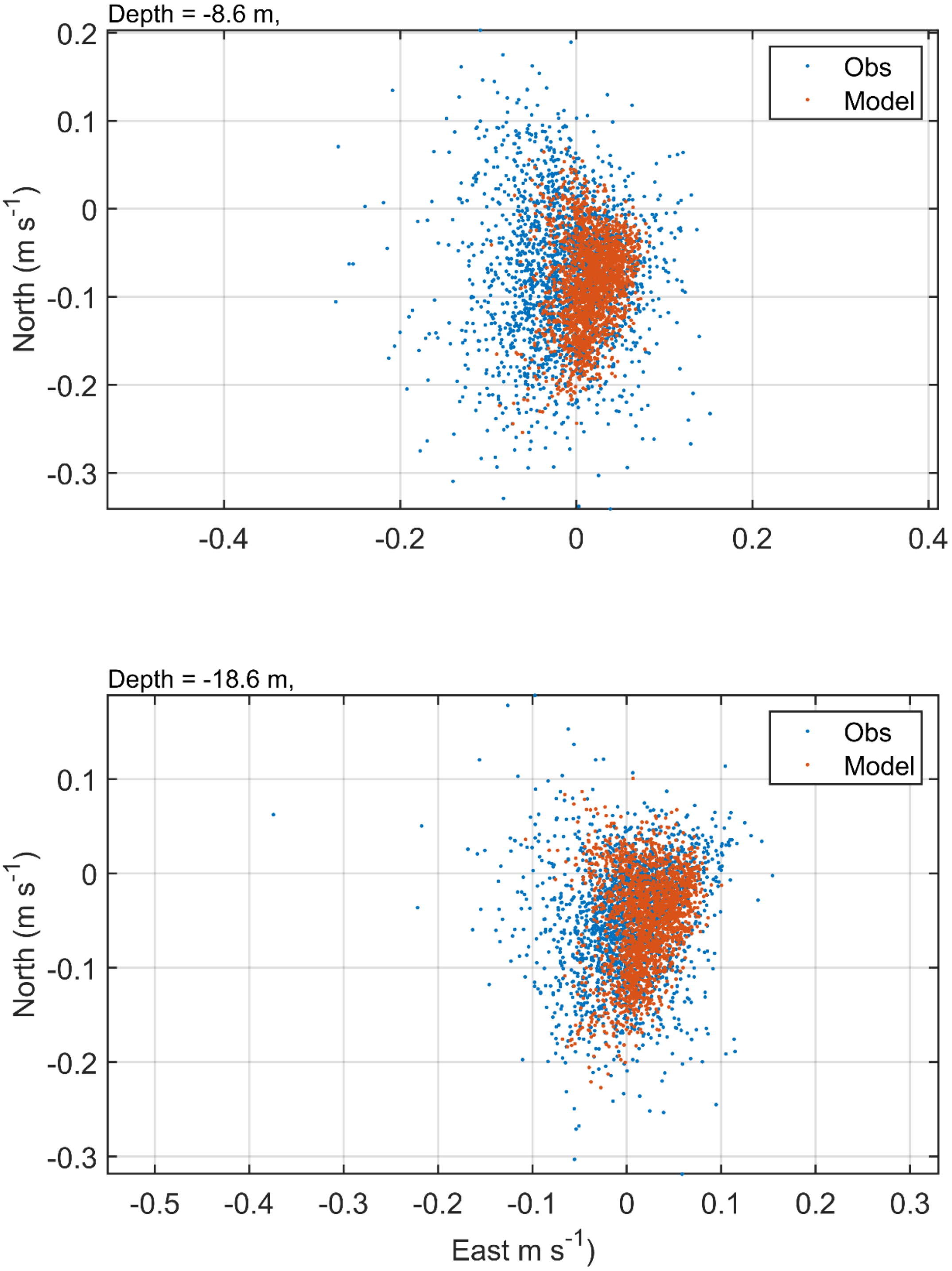


Figure A.4. Scatter plot of observed and modelled velocity at the ADCP location at two depth 8.6m (top) and 18.6m (bottom) from May - August 2019 (ID277). Observed data are in blue, model results in red.

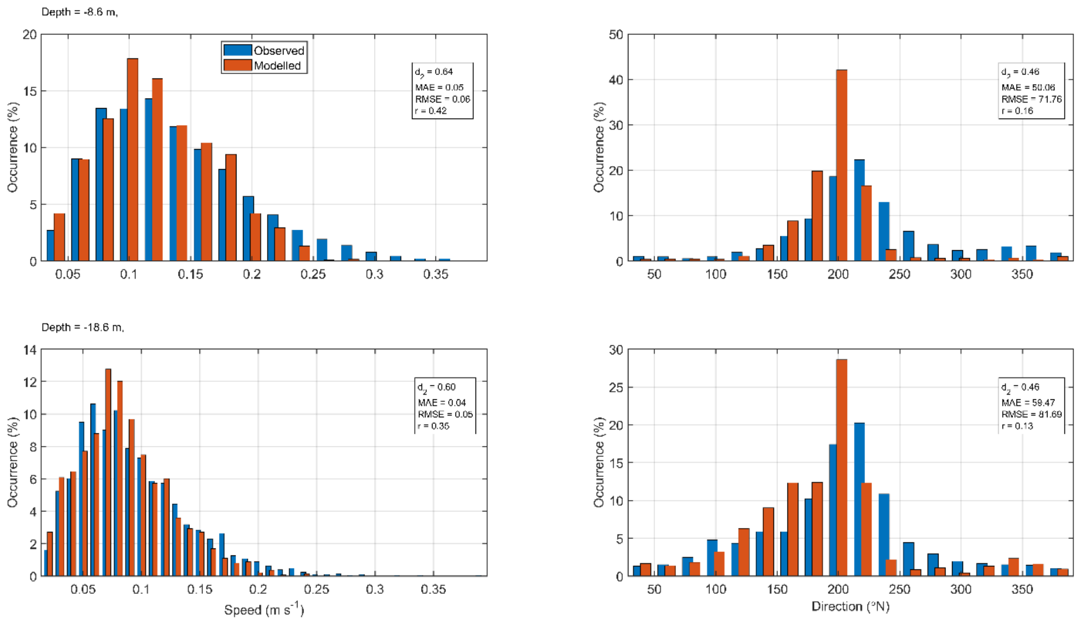


Figure A.5. Histograms of observed and modelled speed (top) and direction (bottom) at the ADCP location at two depths 8.6m (top) and 18.6m (bottom) from May - August 2019 (ID277). Observed data are in blue, model results in red.

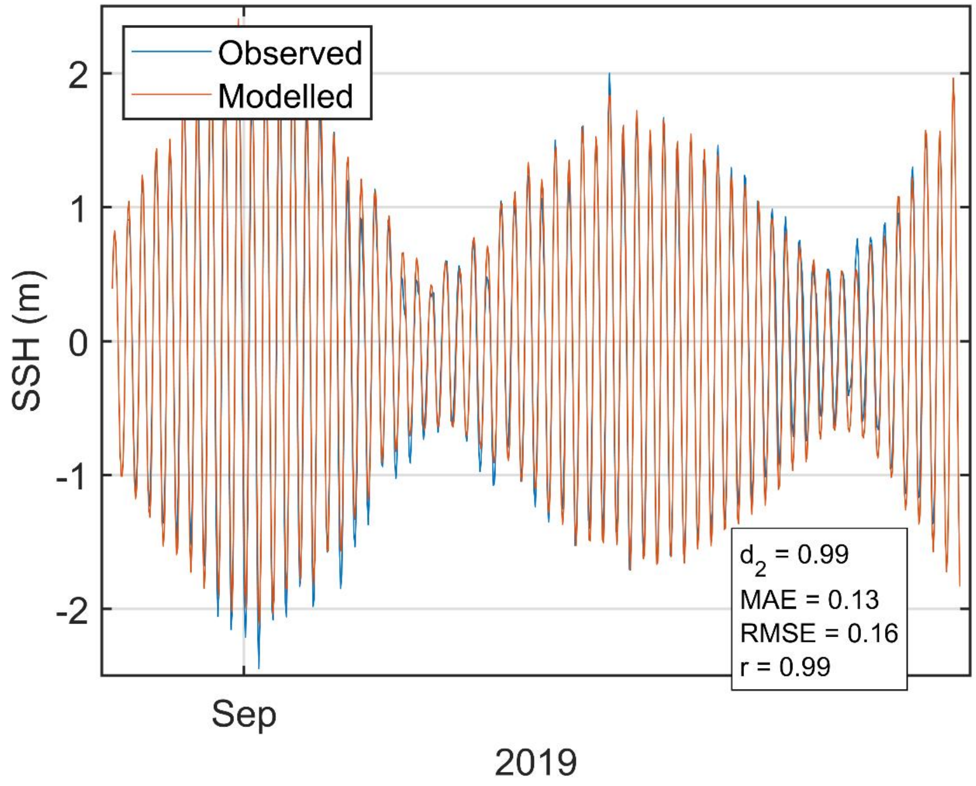
Table A.2. Model performance statistics for sea surface height (SSH), and East and North velocity at the ADCP location from the calibration simulation, May - August 2019 (ID277).

	SSH	East		North	
Depth (m)		8.6	18.6	8.6	18.6
Skill, d_2	0.99	0.47	0.48	0.66	0.66
Mean Absolute Error (MAE)	0.13 m	0.05 m s^{-1}	0.04 m s^{-1}	0.06 m s^{-1}	0.05 m s^{-1}
Root-Mean-Square Error (RMSE)	0.16 m	0.06 m s^{-1}	0.05 m s^{-1}	0.07 m s^{-1}	0.06 m s^{-1}

A.3.2 Comparison, August - September 2019

The model was compared against ADCP data from August - September 2019 (ID282). The comparison looks first at sea surface height, as measured by the ADCP pressure sensors, and secondly at the north and east components of velocity. The results of the comparison exercise are presented in Figures A.6 – A.9 and Table A.3.

Model skill scores were 0.99, 0.49 (-9.2 m depth), 0.53 (-16.2 m depth) and 0.7 (-9.2 m depth), 0.58 (-16.2 m depth) for the sea surface height and East and North components of velocity. RMSE values were 0.19 m, 0.09 m s^{-1} and 0.06 m s^{-1} for SSH and the two components of velocity had values of MAE and RMSE being in the range 4 – 7 cm s^{-1} (Table A.3). The scatter plots and histograms demonstrate that the modelled current had broadly the same magnitude and direction characteristics as the observed data (Figures A.8 and A.9).



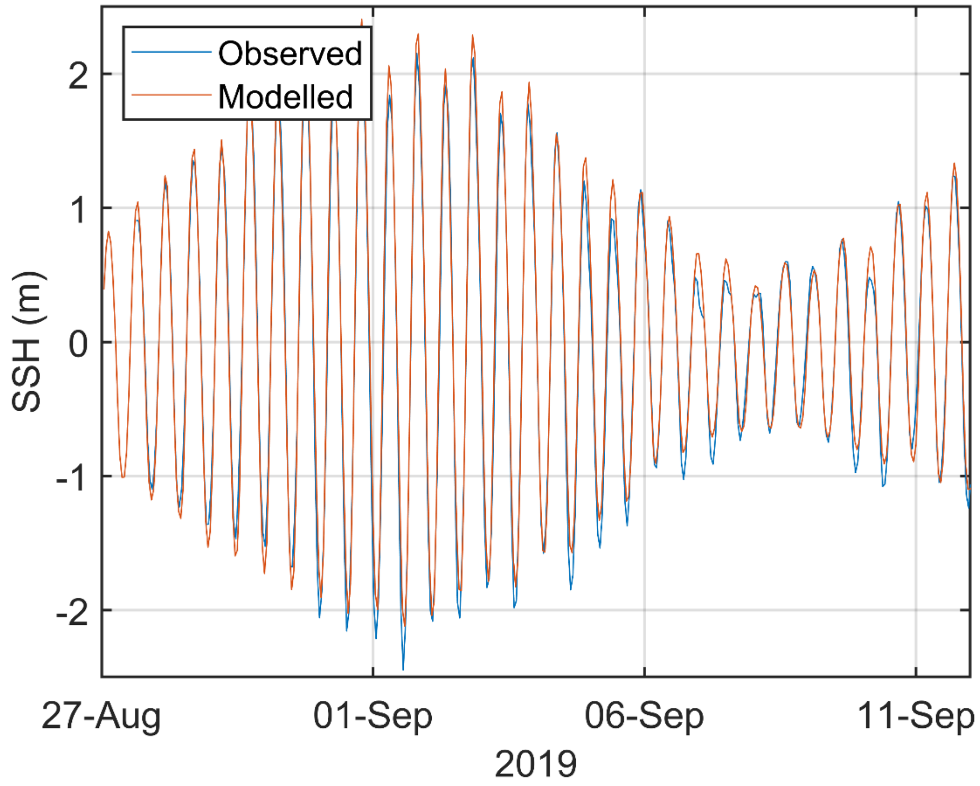


Figure A.6. Comparison between observed and modelled sea surface height at the ADCP location from August – September 2019. Both the full record (top) and a subset of 15 days (bottom) are shown. Observed data are in blue, model results in red.

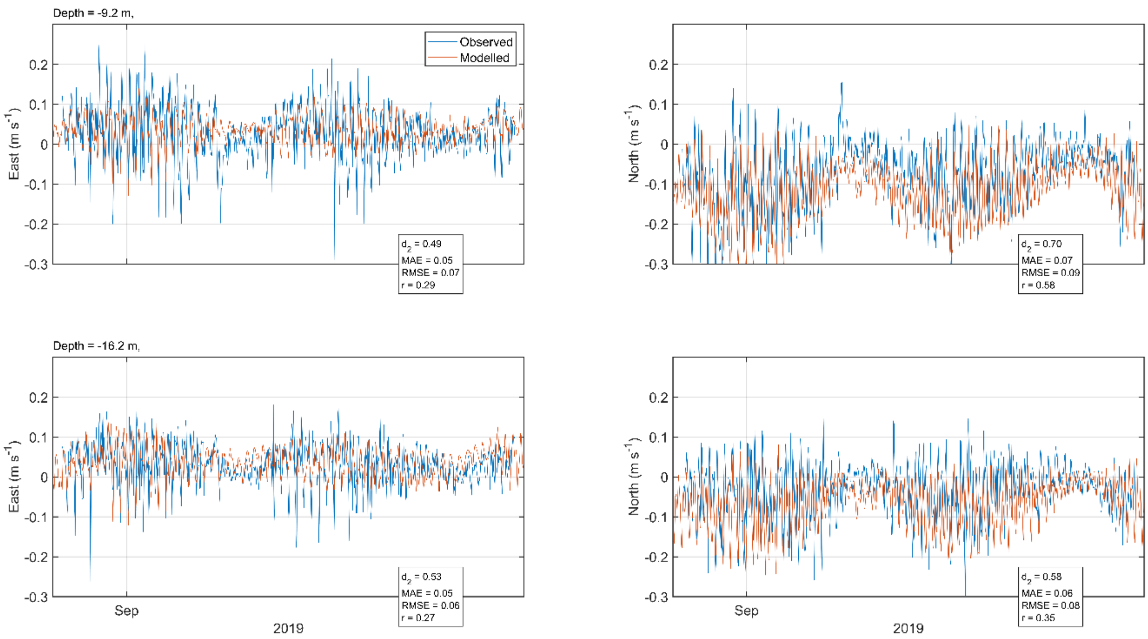


Figure A.7**.** Comparison between observed (ID282) and modelled East (left) and North (right) at two depths -9.2 m (top) and -16.2 m (bottom) components of velocity at the ADCP location for 15 days in 2019. Observed data are in blue, model results in red.

Table A.3. Model performance statistics for sea surface height (SSH) and East and North velocity at the ADCP location from August - September 2019 (ID282).

	SSH	East		North	
Depth (m)		9.2	16.2	9.2	16.2
Skill, d_2	0.99	0.49	0.53	0.7	0.58
Mean Absolute Error (MAE)	0.13 m	0.05 m s^{-1}	0.05 m s^{-1}	0.07 m s^{-1}	0.06 m s^{-1}
Root-Mean-Square Error (RMSE)	0.16 m	0.07 m s^{-1}	0.06 m s^{-1}	0.09 m s^{-1}	0.08 m s^{-1}

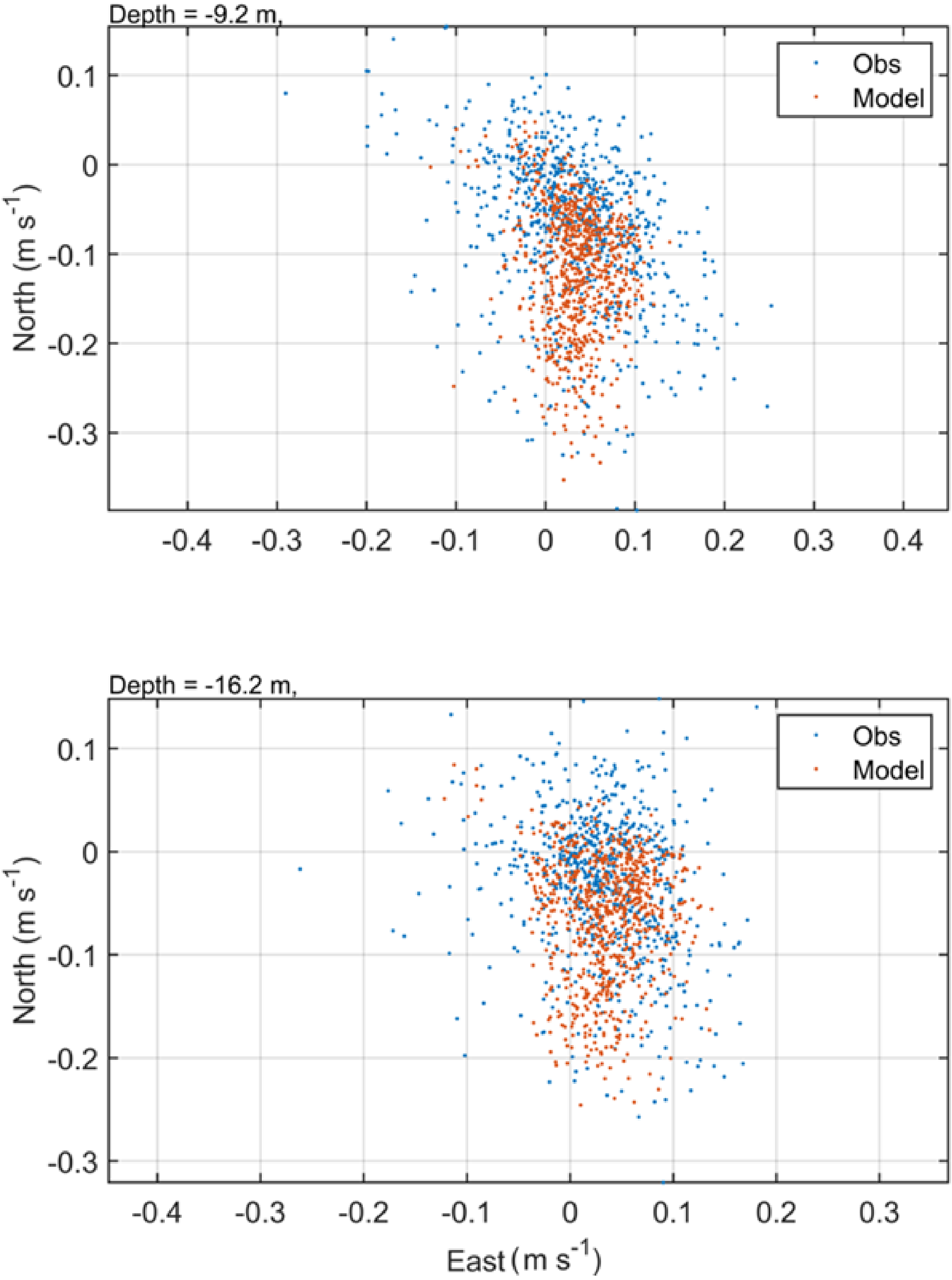


Figure A.8. Scatter plot of observed and modelled velocity at the ADCP location from August – September 2019 (ID282) at two depths -9.2 m (top) and -16.2 m (bottom). Observed data are in blue, model results in red.

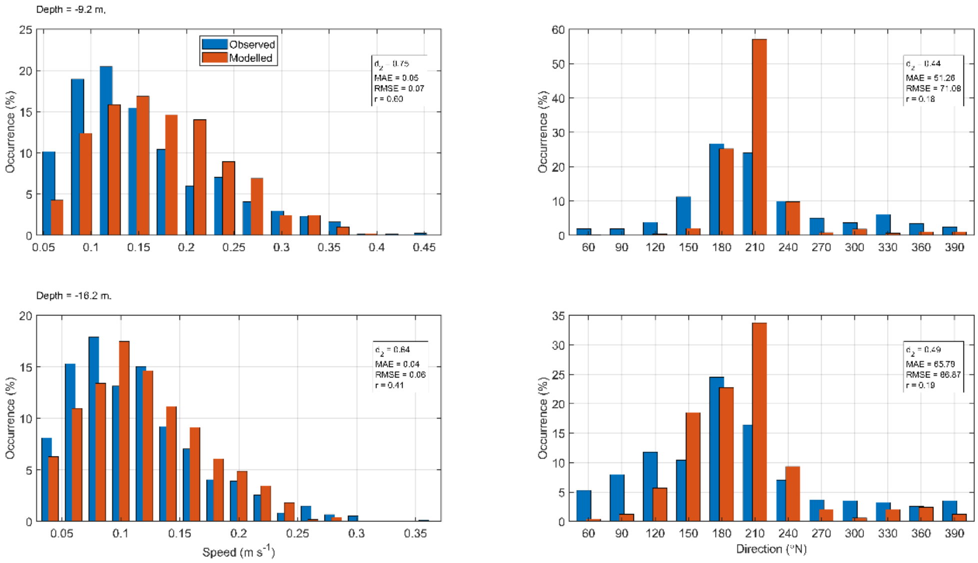


Figure A.9. Histograms of observed and modelled speed (top) and direction (bottom) at the ADCP location from August – September 2019 (ID282) at two depths -9.2 m (top) and -16.2 m (bottom). Observed data are in blue, model results in red.

A.4 Modelled Flow Fields

Modelled flood and ebb velocity vectors at spring tides are illustrated in Figure A.14. The Ardgour (Linnhe) site is exposed to currents where the flow comes down Loch Linnhe into the Corran Narrows on the ebb and up Loch Linnhe on the flood tide. The prevailing currents are South East. The dispersion modelling reflected this regime, with the patches of medicine in every modelled case being transported Southwards out of Loch Linnhe.

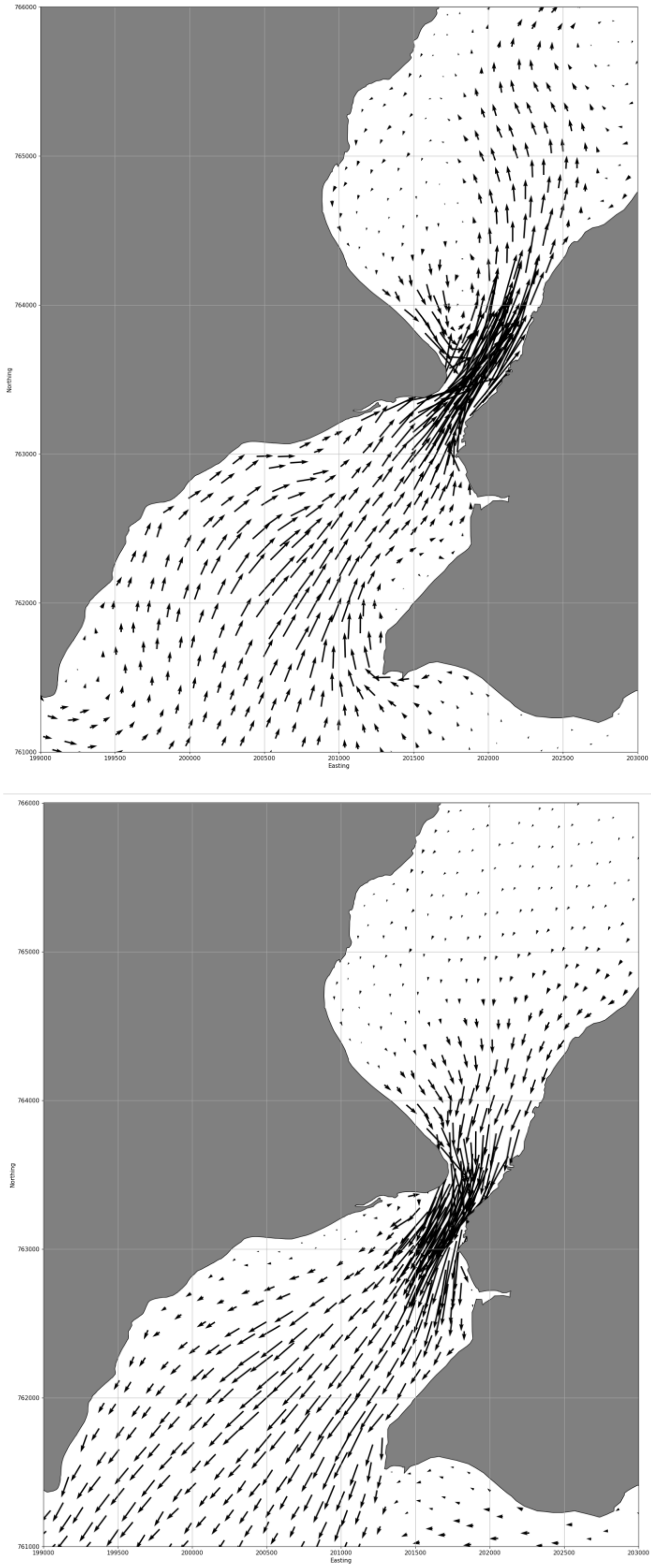


Figure A.10. Modelled flood (top) and ebb (bottom) surface current vectors during spring tides on 3rd August 2019.

A.5 References

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