Marine Modelling Report Chalmers Hope

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1. Summary

This report presents the hydrodynamic and particle tracking model used to simulate the far-field dispersal of solids and dilution of bath treatments at Chalmers Hope. The far-field benthic model highlights the dispersive nature of the proposed Chalmers Hope site, with only a small accumulation of sediment (mean concentration <50 g/m^2) within the 100m mixing zone. When considering the release of particulate waste from all sites within the west Scapa flow domain, less than 1% of the identified PMF's area is impacted. This suggests the cumulative risk to these sensitive regions is insignificant. The cumulative benthic impact for all sites within west Scapa Flow provides an impacted area equal to 1.78 km^2 – this is equivalent to 0.68% of the Scapa Flow waterbody area. The proposed Chalmers Hope site is shown to contribute 0.42 km^2, resulting in a contribution of 23.6% to the west Scapa Flow cumulative impact area. For context, the existing Chalmers Hope site contributes 0.15km^2 (10.1%) to the cumulative impact area. The extent of the impacted areas is considered to be an overestimation as particle parameters were assigned using conservative estimates and the site are stocked using a maintained maximum biomass.

Bath treatments were simulated using particle releases designed to replicate realistic treatment regimes, this used 3 treatments per day with a 3 hourly interval. For Azamethiphos, a recommended consent mass of 785 g per 24 hour period and 466.67g per 3 hour window was shown to be compliant with EQS. This equates to a treatment volume of 1.7 wellboat treatments (1,500 m^3 capacity) per 3 hour period when using the repeat treatment mass. Cypermethrin achieved a recommended consent mass of 0.059925g per 3 hour period. This treatment quantity is not viable for the effective treatment of sea lice. Deltamethrin provided a recommended consent mass of 40 g per 3 hours while maintaining below EQS. This provides a treatable volume equal to 13.3 wellboat treatments (1,500 m^3 capacity) per 3 hour period.

The isolated impacts associated with Chalmers Hope shows small impact areas that remain below the calculated mixing areas for the relevant EQS times and concentrations. When cumulative impacts are assessed, Chalmers Hope is shown to have a minor contribution to the wider impact area. The numerical simulation of bath treatments has shown successful treatment options using Azamethiphos and Deltamethrin. The application of these treatments is shown to be compliant with all EQS and MAC restrictions.

The results of the far field deposition and the bath treatments are summarised in Table 1.

Table 1. Summary of far field and bath treatment results

Stocking details			
Maximum biomass (Tonnes)	2,500	Stocking Density (Kg/m^3)	15.15
Pen Layout			
No. pens	12		
layout	2 x 6		
Circumference (m)	120		
Mooring grid (m)	70		
Orientation (deg)	315		

Far-field benthic deposition		
Waterbody area (km^2)	263.3	
PMF area (km^2)	11.36	
	Existing site (1,000 t)	**Proposed site (2,500 t)**
Percentage waterbody area impacted (%)	0.57	0.68
Impacted PMF area (km^2)	0.002	0.009
Percentage PMF area impacted (%)	0.02	0.08
Cumulative impact area (km^2)	1.49	1.78
Cumulative impact area difference – proposed vs. existing (km^2)	0.29	
Cumulative impact area percentage difference – existing vs. proposed (%)	19.46	
Bath Treatments		
Azamethiphos		
Consent mass - 3hr (g)	466.67	
Consent mass – 24hr (g)	785	
Cypermethrin		
Consent mass – 6hr (g)	32 (0.11985)	
Deltamethrin		
Consent mass – 6hr (g)	80	

2. Introduction

2.1 Site Details

Chalmers Hope is an existing, consented site (CAR/L/1003062/V6) operated by Cooke Aquaculture Scotland. The site is located towards the western entrance of Scapa Flow, on the north-east coastline of Hoy, Orkney (Figure 1). Currently, the site has a maximum consented biomass of 1000 tonnes, across 12 pens, with a 90 m circumference and net depth 10 m, arranged in 50 m mooring grids. This is equivalent to a stocking density of 12.94kg/m^3 during peak biomass.

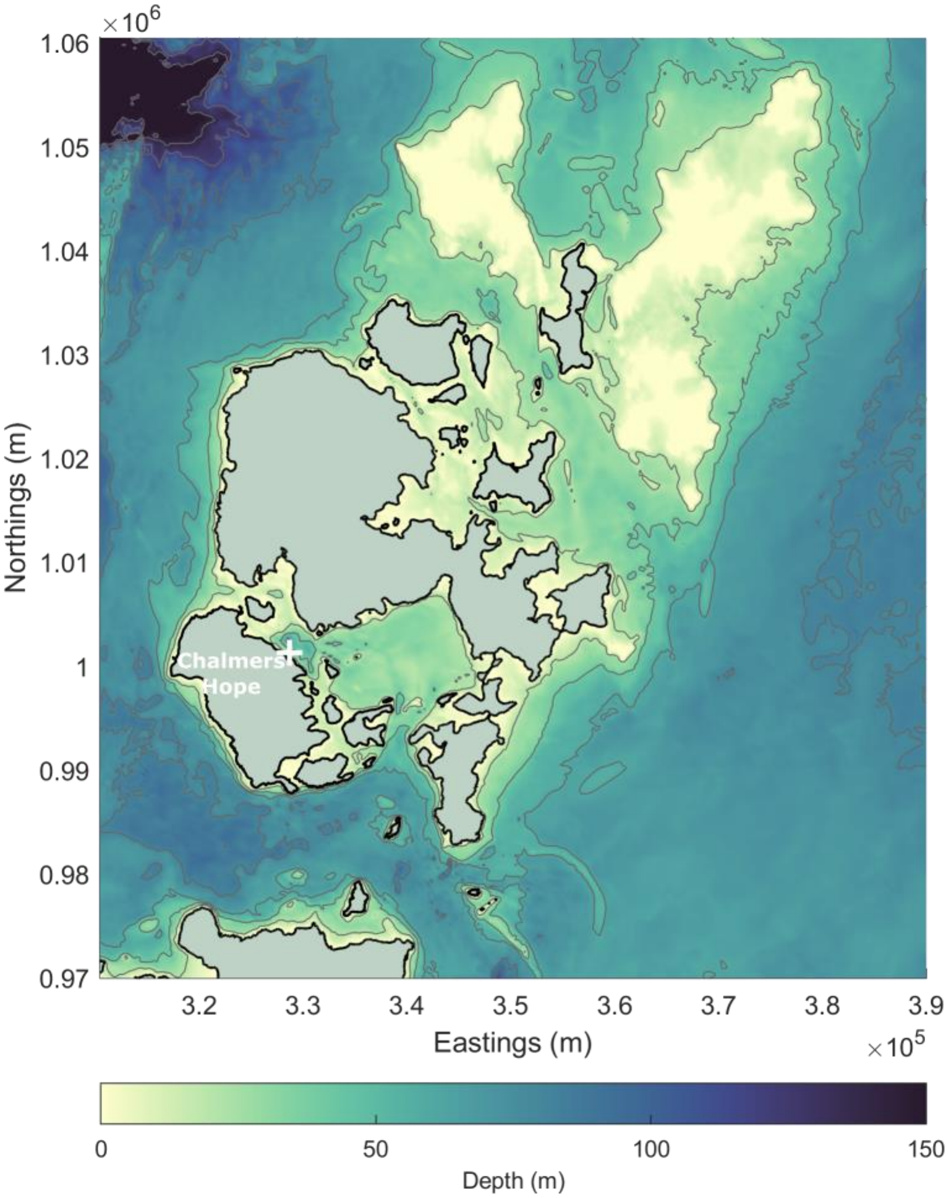


Figure 1. Site location and bathymetry with depth contours at 20m intervals.

The proposed development at Chalmers Hope replaces all existing infrastructure and repositions the site in deeper water, 250m to the NNE (328735 E, 1001311 N). Here, 12 pens with an increased circumference of 120m and net depth of 12m arranged in 70m mooring grids are proposed. Benthic modelling using the SEPA default NewDepomod model iterated a maximum biomass of 2500 tonnes at the newly proposed site, which was compliant with all EQS. This equates to a stocking density of

15.15kg/m^3 during peak biomass. Further information on the existing and proposed site infrastructure and pen layout is presented in Table 2.

Table 2 – Site infrastructure and pen layout.

	Chalmers Hope (existing)	**Chalmers Hope (proposed)**
Consent number	CAR/L/1003062/V6	CAR/L/1003062
Company	Cooke Aquaculture Scotland	Cooke Aquaculture Scotland
Receiving water	Scapa Flow	Scapa Flow
Site centre (OSGB36)	328607 E, 1001109 N	328735.3 E, 1001310.7 N
Current meter location (OSGB36)/ year of deployment	328750 E, 1001162 N / 2003	328663.5 E, 1001218.7 N / 2016 328688 E, 1001269 N / 2018
Distance to shore (km)	0.18	0.41
Average water depth (m)	20.9	34.16
Maximum biomass (t)	1000	2500
Total number of pens	12	12
Number of pen groups	1	1
Formation	2 x 6	2 x 6
Pen group orientation (°)	320	315.2
Pen circumference (m)	90	120

The coastline surrounding the site varies, with large rocky cliffs towards the north, and a small sandy/pebbly embayment towards the south. Directly offshore from the proposed site is Bring Deeps, a large, scoured bathymetric depression with depths exceeding 50m. Hydrographic data spanning a 90-day period, collated from two individual ADCP deployments, reveals a strong tidal influence at the proposed site, with flow velocities regularly exceeding 0.1m/s, suggesting highly dispersive conditions. Current and elevation timeseries show strong semi-diurnal and spring-neap temporal variability. Vertical velocity profiles reveal current speed is generally greatest in the cage bottom layer (mean = 0.131m/s) and residual current speed is greatest in the near bed layer (0.022m/s). A more detailed description of hydrographic data collection and analysis is given in the Chalmers Hope modelling data collection report (Greenwood, 2019).

2.2. Objectives of the Modelling Study

Given the existence of several closely situated licensed aquaculture sites within Scapa Flow and the recognition of multiple sensitive marine features in the receiving water body, it is pertinent to explore the cumulative effects of farm discharges on the wider environment. A high resolution MIKE21 hydrodynamic model is used to simulate the flow dynamics across Orkney. The results of which are applied to force numerous MIKE21 particle tracking models which, in turn, are used to predict the potential environmental influence of discharges from the proposed Chalmers Hope site and its neighbouring sites. Maps and EQS results are presented to show the predicted spread of particulate waste matter and bath treatment medicines, and to infer their potential impact, particularly on sensitive marine features highlighted in the Chalmers Hope Screening modelling and risk identification report by SEPA (2020).

3. Model Description and Configuration

DHI's Mike21 is used to simulate solid waste (feed and fish faecal matter) and bath treatment medicine dispersion from the proposed Chalmers Hope site. This uses a calibrated hydrodynamic and particle tracking models to replicate particle emissions from all farms identified within the Screening and Risk Identification report. This utilises better performing spatially varying hydrodynamics to identify particle fate and accumulation near existing farms and sensitive marine features (Table 3).

Table 3. Farm and sensitive marine features identified with the west Scapa Flow.

Name	Feature type	Location (OSGB)		Maximum mesh resolution (m^2)
		East (m)	North (m)	
Brings Head	Fish Farm	327300	1002200	1296 (36m)
Chalmers Hope	Fish Farm	328735	1001311	1296 (36m)
Lyrawa Bay	Fish Farm	329900	998900	1296 (36m)
Pegal Bay	Fish Farm	330200	997600	1296 (36m)
South Cava	Fish Farm	333300	998900	1296 (36m)
West Fara	Fish Farm	332100	995300	1296 (36m)
Ore Bay	Fish Farm	331600	994200	1296 (36m)
Toyness	Fish Farm	335400	1003700	1296 (36m)
Maerl or coarse shell gravel with burrowing sea cucumbers	PMF - Point	329893	1002316	2000 (45m)
Maerl beds	PMF - Area	Shapefile		2000 (45m)
Horse mussel beds	PMF - Area	Shapefile		2000 (45m)
Flame shell and horse Mussel beds	PMF - Area	Shapefile		2000 (45m)

3.1 MIKE21 Hydrodynamic Model

This study uses DHI's Mike21 FM model to simulate free-surface flow in a coastal environment. The model uses a flexible mesh to replicate tidal hydrodynamics, wind and wave driven currents, and storm surges.

The model solves the two-dimensional incompressible Reynolds averaged Navier-Stokes equations, using the Boussinesq and hydrostatic pressure assumptions to simulate 2D hydrodynamics over the domain. Continuity of momentum, temperature, salinity and density are applied alongside the k-epsilon turbulent closure scheme. A cell centred finite volume approach is applied for the spatial discretion of the momentum equations. This is applied over a cartesian two-dimensional unstructured grid (mesh).

3.1.1 Model Domain

The model boundaries, shown in Figure 2A, surround Orkney and the northeast coast of mainland Scotland. The model domain is created using the cartesian Ordnance Survey of Great Britain 1936 coordinate system (OSGB 1936). Coastline data is imported from Ordnance Survey (2020) and is used to define the land boundaries within the domain. Bathymetry data are taken from the UK Hydrographic Office (UKHO, 2021). A flexible mesh is applied, containing 90,158 nodes and 171,625 elements. The peripheries of the model domain have a coarse resolution, with an approximate cell spacing of 2km. Mesh resolution increases in regions of specific interest (e.g. licensed sites and

PMFs) or where complex flow patterns are expected. For example, the area between farms and PMF's in Bring Deeps has a maximum mesh resolution of 2500m^2 (50m) (Figure 2B). More details on mesh resolution at sites and PMF's is provided in table 3.

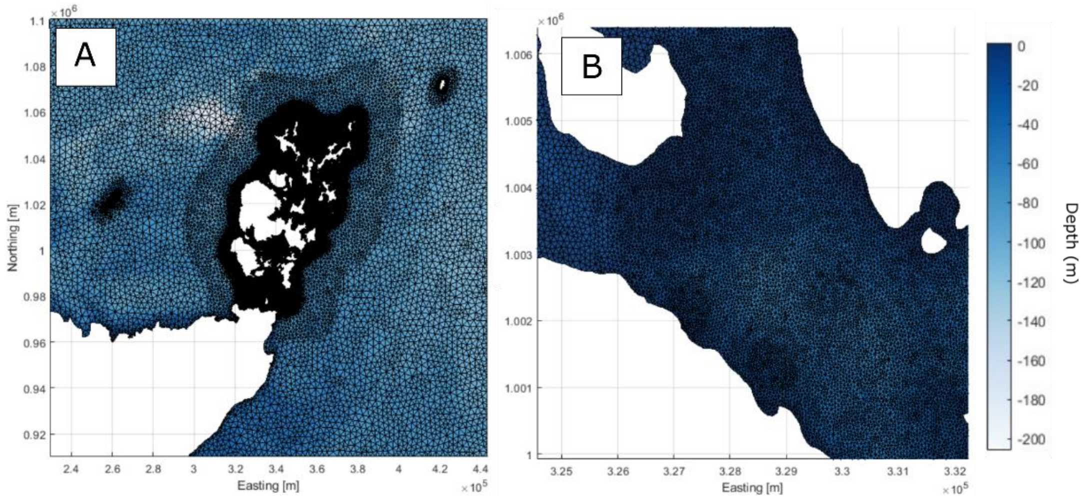


Figure 2. A: wider computational mesh. B: Computational mesh around the proposed Chalmers Hope site.

3.1.2 Configuration and Boundary Forcing

Boundary conditions are taken from DHI's global tidal model, where tidal elevations are calculated from 10 principal astronomical constituents (Semidiurnal M2, S2, K2, N2, Diurnal S1, K1, O1, P1, Q1 and Shallow water M4). The global tidal model has a resolution of 0.125°x 0.125° and interpolates data to the nearest boundary element. Temporal resolution outputted elevations every 12 mins. Wind data was taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 model (ECMWF 2020). This provides wind velocity in U and V components, as well as surface pressure with a resolution of 0.25°x. 0.25° at a 3-hourly interval.

A 2- dimensional domain is proposed with a time step interval of 60 s, with point data outputs at 10 min (600 s) intervals and area data outputs at 60 min (3600 s) intervals. The model is run for 365 days, plus an additional 5 days to allow the hydrodynamic model to stabilise. The governing equations use the shallow water equations with high order time integration and spatial discretization. Minimum and maximum timesteps were relaxed to 0.01s and 60s with a critical CFL number of 0.95. Flooding and drying were included, with a drying depth of 0.005 and a wetting depth of 0.1. The horizontal eddy viscosity applies Smagorinsky's formulation with a constant value of 0.28. Bed roughness in the form of the Manning number is used as the main calibration term. This parameter is adjusted to calibrate the model.

3.1.3 Calibration and Validation

The model was calibrated using Acoustic Doppler Current Profiler (ADCP) data from sensors deployed within 150 m of the site centre. For calibration, the measured surface elevation and depth averaged velocity was compared to the model outputs. Data statistics are presented to quantify model performance. The model was then validated against a separate measured dataset, covering a different time period. This section provides a brief overview of the calibration and validation procedures and results, a more detailed discussion is provided in the Chalmers Hope Marine Modelling Methods Statement (Greenwood, 2021).

3.1.3.1 Calibration

The calibration process adjusts the dissipative forcing within the model to compare with observed data. The calibration of the Chalmers Hope hydrodynamic model took place from 01/10/2016 to 18/10/2016, using data from an ADCP deployed at 328663.5 E, 1001218.7N. A simulation spin-up time of 48 hours was used. The bed resistance was adjusted to ensure the best fit between the observed and modelled water level and current speed. A Manning number of 31 $m^{1/3}/s$ provided optimum results. For the initial calibration and validation, the model included wind boundary forcing.

The statistical parameters for the calibration period are shown in table 4. MSL shows excellent phase agreement with a Pearson correlation of 0.985 and mean error values indicating a small deviation of the model and the observed data. The component east and north velocities are inherently more variable in nature than MSL, meaning velocities are more difficult to predict. Therefore, larger variations exist between modelled and observed velocities than for MSL, however statistics still indicate an acceptable degree of agreement. Overall, the model performs well and provides a good agreement with in situ data.

Table 4. Statistical analysis of the calibrated model.

	MSL	**East**	**North**
Mean absolute error	0.151 m	0.058 m/s	0.038 m/s
RMS error	0.169 m	0.092 m/s	0.058 m/s
NRMSE (range)	0.045	0.125	0.114
Correlation	0.985	0.692	0.750

3.1.3.2 Validation of short-term model

Validation demonstrates the model accuracy by comparing simulated results with an independent observed dataset. An initial, short-term model validation used a second separate ADCP deployment from 17/06/2018 to 04/07/2018, covering 17 days. The assessment of the model performance uses the same MSL and east and northerly velocity components. Tidal and wind boundary forcing were updated to match the deployment period where the same bed friction value was applied.

The results of the MSL validation indicate a good agreement between the observed and modelled data. The MSL shows a similar statistical correlation and error magnitude to that of the calibration. The east and north velocity components experience an improvement in model performance with lower RMS error values, indicating a more representative model. The statistical results of the initial, short-term validation period are shown table 5.

Table 5. Statistical analysis of the validated short-term hydrodynamic model**.**

	MSL	**East**	**North**
Mean absolute error	0.163 m	0.033 m/s	0.023 m/s
RMS error	0.193 m	0.05 m/s	0.031 m/s
NRMSE (range)	0.073	0.092	0.108
Correlation	0.965	0.927	0.909

3.1.3.3 Validation of long-term model

The far-field benthic solid dispersion is simulated using a yearlong model. This simulates tidal elevation and current speeds from 30/12/2017 to 01/01/2019. The same model parameters as the previous calibration and validation are applied. However, to avoid any sporadic influence from local weather conditions, the wind boundary forcing was removed. This is only possible as the wind is shown not to be a dominant source for driving surface currents (Greenwood, 2020).

The validation period for the long-term model covers 63.9 days from 31/05/2018 to 03/08/2018. As wind boundary forcing have been removed from the model, harmonic analysis is applied to the ADCP validation dataset to extract the tidal flow components. The results of the validation are shown in figures 3 and 4, with the statistical comparison in table 6. This shows a very good agreement between the model and measured dataset, where performance has improved when compared to the initial short-term calibration and validation results.

Table 6. Statistical analysis of the validated long-term hydrodynamic model without wind forcing.

	MSL	**East**	**North**
Mean absolute error	0.147 m	0.021 m/s	0.011 m/s
RMS error	0.173 m	0.026 m/s	0.013 m/s
NRMSE (range)	0.054	0.064	0.054
Correlation	0.973	0.981	0.984

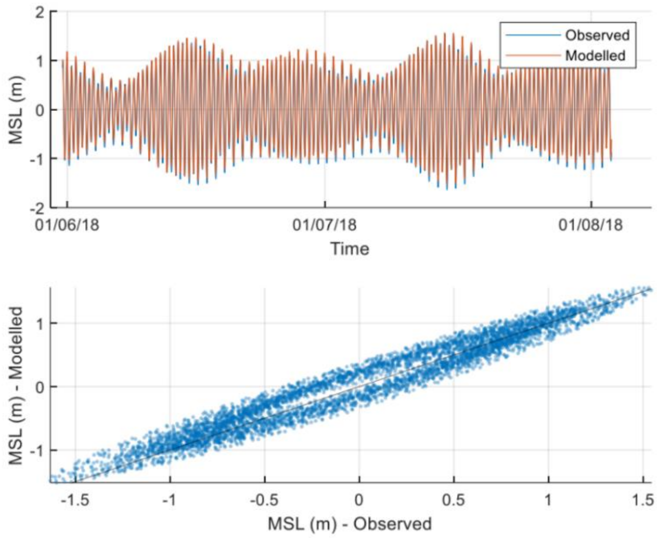


Figure 3. Mean sea level model validation from the 31/05/2018 to the 03/08/2018.

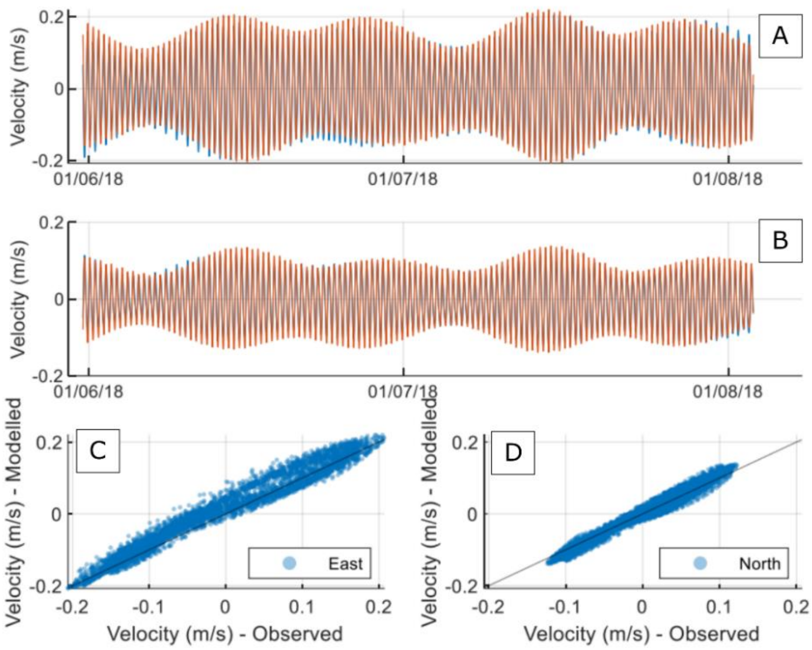


Figure 4. East (A&C) and north (B&D) velocity components for the validation period of 31/05/2018 to the 03/08/2018.

3.1.4 Drogue and Dye Release Study and Model Particle Behaviour

To allow an assessment of horizontal dispersion at the proposed Chalmers Hope site, a series of drogue and dye release experiments were conducted by Anderson Marine Surveys on 12/06/2021. A tracer dye, Rhodamine WT, was released at the water's surface during flooding tides, ebbing tides and slack water. Monitoring and tracking of the resultant dye plumes was achieved using a survey vessel recording fluorescence along a series of transects through the plume. The simultaneous release of drogues equipped with inbuilt GPS loggers provided additional insight into the Lagrangian velocity field. A bottom mounted ADCP was also installed adjacent to the survey site, recording hydrographic data throughout the survey period. A detailed description of methodology and dispersion measurements are given in the report by Anderson Marine (2021).

The dye/drogue data allowed calibration of the horizontal dispersion coefficient (K_h) within the offline MIKE21 particle tracking model, full details of which are given in the Chalmers Hope dispersion coefficient calibration report. Figures 5 and 6 show a subset of the modelled and observed dye and drogue data. High wind speeds (>20mph) blowing from the west were recorded during the survey period (Weather Underground, 2021). Given the surface confinement of the dye and the large above-surface structure of the drogues, their dispersal appears to be greatly affected by the wind. During the flood tide the wind direction and tidal flow direction are roughly aligned, resulting in a constructive impact where the dye and drogues are advected further than would be expected by the tidal currents alone – as is the case represented by the model results. During the ebb tide, wind direction and tidal currents act in opposite directions, both the centre of the dye patch and drogues are observed to travel in a SE direction despite a NW ebbing flow.

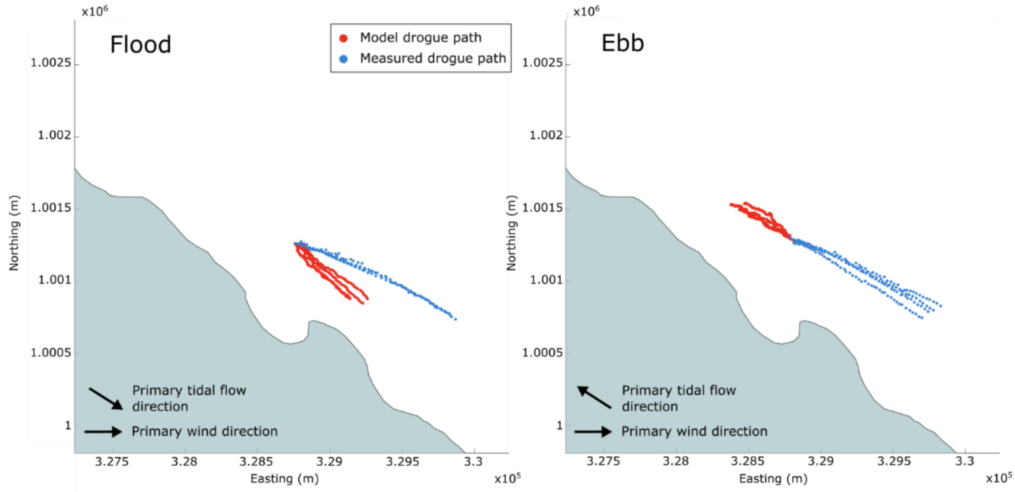


Figure 5. Modelled (red) and measured (blue) drogue paths. Model K_h = 0.1 m^2/s .

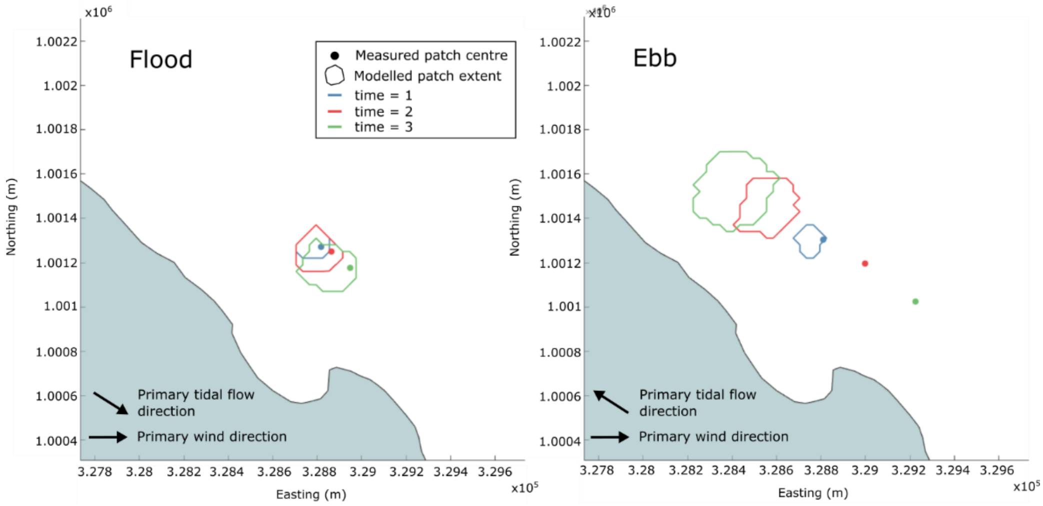


Figure 6. Modelled (outline) and measured (filled circle) dye patch dispersal and advection through time. Model K_h = 0.1 m^2/s .

The particle tracking model was run using several different K_h values ranging from 0.01 m^2/s to 5 m^2/s. Calibration of the dispersion and advection performance of the model was undertaken by comparing the normalised modelled concentration of dye particles and the normalised measured fluorescence of the dye at matching points in time and space along the vessel transects. The effect of the wind made the ebb model runs and data incomparable, therefore only dye released during the flood tide were considered. The results of the calibration procedure are given in table 7.

Table 7. Dye plume dispersion calibration results

Horizontal dispersion coefficient (K_h)	**Correlation**	**Mean absolute error**	**RMS error**	**Gradient**	**Intercept**
0.01	0.39	0.066	0.159	0.364	0.045
0.1	0.48	0.066	0.161	0.377	0.039
0.2	0.51	0.065	0.156	0.405	0.034
0.3	0.53	0.066	0.155	0.415	0.029

0.4	0.54	0.067	0.156	0.42	0.024
0.5	0.55	0.068	0.158	0.421	0.02
1	0.58	0.081	0.171	0.416	0.006
5	0.58	0.121	0.208	0.372	-0.005

Table 7 shows model performance improves with increasing K_h values from 0.01 m^2/s to 0.3 m^2/s, with gradually increasing correlation coefficients and decreasing RMS and mean absolute errors. Model performance decreases when K_h values exceed 0.3 m^2/s, as shown by an upward trend in error values between 0.3 m^2/s and 5 m^2/s. For a K_h value of 0.3 m^2/s a correlation coefficient of 0.5 and RMS error of 0.155 were achieved, these values are not indicative of a highly accurate model. This is because atmospheric forcing was not included in the hydrodynamic model, but clearly plays a role in dye advection and dispersion.

As illustrated in figures 5 and 6, wind greatly impacts dye dispersion and therefore the dispersion coefficient. The most realistic value for K_h, at any one location, will greatly vary through time as it is dependent on the prevailing weather conditions, amongst other factors. During the sampled period with increased wind speeds, a K_h value of 0.3 m^2/s gave the best agreement, but for periods of lower wind speeds dispersion is likely to be reduced. To account for this temporal variability and prevent over-prediction of dispersion within the model, it is considered more appropriate to use a lower K_h value of 0.1 m^2/s to better represent average conditions through time.

3.2 MIKE21 Benthic Model

Waste feed and fish faecal matter dispersion is simulated using DHI's particle tracking model. This was run decoupled from the long-term hydrodynamic model described in section 3.1. The mesh and timestep are identical to those used within the hydrodynamic model, however the simulation start time of the particle tracking model is delayed until after the hydrodynamic model warm-up period, allowing flow fields to fully establish.

3.2.1 Particle Configuration

Each farm specified in table 3 is modelled at peak biomass for the entire 365 day model duration. To simulate waste feed and faeces, two particle classes are specified for each farm. This allows separate particle parameters to be applied to each particle type. Peak biomass is used to calculate the feed waste and faecal matter using the following equations and values in table 8. The calculated quantities of waste and excreted solids for each farm are given in table 9. It should be noted that for completeness Ore Bay is assumed to be stocked and is included in the benthic modelling presented here. However, the site has been fallow for a number of years and is unlikely to be used in the future.

Table 8. Input feed parameters

Parameter	Symbol	Value
Feed requirement	f_r	7kg per tonne biomass per day
Feed water (%)	f_h	9%
Feed waste (%)	f_w	3%
Feed absorbed (%)	f_a	85%
Feed carbon (%)	f_c	49%
Faeces carbon (%)	f_f	30%

The amount of waste solids (w_s) per day is calculated as

$$w_s = (1 - f_h).f_w.f_r$$

Waste carbon (w_c) is calculated as

$$w_c = (1 - f_h).f_c.f_w.f_r$$

Excreted solids (e_s) are calculated as

$$e_s = (1 - f_h).(1 - f_w).(1 - f_a).f_r$$

Excreted carbon (e_c) is calculated as

$$e_c = (1 - f_h).(1 - f_w).(1 - f_a).f_f.f_r$$

Table 9. Particle mass per model timestep.

Site	Biomass (t)	Waste feed (kg)	Excreted Solids (kg)
Chalmers Hope (proposed)	2500	19.90625	96.54531
Chalmers Hope (existing)	1000	7.9625	38.618125
Brings Head	968	7.7077	37.38235
Lyrawa Bay	400	3.185	15.44725
Pegal Bay	400	3.185	15.44725
South Cava	2500	19.90625	96.54531
West Fara	800	6.37	30.8945
Toyness	1343	10.69364	51.86414
Ore Bay	450	3.583125	17.37816

Particle properties are defined in table 10. Waste feed and faeces particle settling rates are defined using the SEPA default values. The results of the drogue and dye release model calibration study were used to determine representative horizontal dispersion coefficients (K_h). During high winds, the data collected indicated an optimal K_h value of 0.3m^2/s. As the effect of the wind resulted in a more dispersive environment, a lower K_h value of 0.1 m^2/s was recommended. This value is applied with a vertical dispersion coefficient of 0.001 m^2/s.

Table 10. Benthic model particle parameters

Particle class	Waste feed	Excreted solids
Decay (s)	0	0
Settling velocity (m/s)	0.095	0.035
Horizontal dispersion (m^2/s)	0.1	0.1
Vertical dispersion (m^2/s)	0.001	0.001
Erosion threshold (N/m^2/s)	0.02	0.02

Throughout the model run period, at every timestep ten particles are introduced into the model domain from an area source. As it is not feasible to define each individual pen manually, a rectangular area for each cage group is defined using the central locations of the corner pens. Particles are randomly released across this rectangular source area in a vertical layer spanning from the sea surface to the depth of the cage bottom. This offers the most representative particle dispersion where concentration and area coverage are most similar to the individual pen simulation.

3.2.3 Environmental Standards (EQS)

Benthic risk is determined using the environmental quality standards outlined in SEPA (2020) (table 11). This will be considered for all farm and marine features. Benthic impact area is determined using the Infaunal Quality Index (IQI), where a relationship between sediment flux and IQI is defined as a proxy for environmental impact. This states that a solid flux of 250g/m^2 is equivalent to an IQI of 0.64. Therefore, any deposition above the 250g/m^2 is defined as having a significant impact on the seabed. The 100m composite mixing zone is defined as the pen area plus an additional 100m buffer zone. An additional intensity standard is applied that restricts the mean concentration of the impacted area dependent on the wave exposure index.

Table 11. Benthic EQS parameters

Benthic		
Pen-edge	Intensity	Mean deposited mass within the 250 g/m^2 impact area should not exceed 2000 g/m^2 where wave exposure is less than 2.8, and 4000 g/m^2 where wave exposure is more than 2.8.
Mixing zone	Area	Total area (m^2) with a mean deposited mass in excess of 250 g/m^2 should not exceed the 100 m composite mixing zone area (m^2). If wave exposure is 2.8 or above, the mixing area may occupy 120% of the 100m mixing zone.

3.3 MIKE21 Bath Model

Particle release is simulated using DHI's Particle tracking model. This is run decoupled from the hydrodynamic model. The mesh and time step remain identical from those used within the hydrodynamic model. However, simulation start time is located out with the hydrodynamic warm-up period and coincides with bath treatments finishing on the spring and neap tides.

3.3.1 Particle Configuration

As treatment chemicals decay when dissolved in aqueous solution, particle decay is included within the model. This decay is specified as the chemical half-life ($t_{1/2}$). This is used to calculate the mean lifetime of the chemical (τ), which is specified within the model as the maximum particle age.

$$\tau = \frac{t_{1/2}}{\ln(2)}$$

At this stage, the particle mass is set to 0kg.

To specify the particle decay within the model, the half-life must be converted to decay rate (λ). This is calculated as

$$\lambda = \frac{0.693}{t_{1/2}}.$$

For Azamethiphos, a half-life of 5.6 days is specified. This corresponds to a mean particle lifetime of 8.08 days with a decay rate of $1.43x10^{-6}$ /s. For Cypermethrin and Deltamethrin, no chemical half-life is available, therefore no chemical decay is simulated for these treatments.

As chemical treatments are dissolved, particle settling within the model was switched off and the erosion critical shear stress was set to 0 N/m^2.

The results of the drogue and dye release model calibration study were used to determine representative horizontal dispersion coefficients. In high winds an optimal K_h value of $0.3m^2/s$ was calculated. As the effect of the wind resulted in a more dispersive environment, a lower more conservative value of 0.1 m^2/s was recommended. This value is applied within the bath treatment model with a vertical dispersion coefficient of 0.001 m^2/s.

3.3.2 Particle Source

Particles are released using an area source within the particle tracking model. As the treatment of individual pens in succession is not feasible within MIKE21, a central representative pen is used for all treatments. Particles are released at a depth of 1.5 m with a layer thickness of 3 m. This replicates a 3 m net depth during treatment.

3.3.3 Treatments

In order to realistically simulate the treatment process, particle releases will be timed to coincide with expected treatment intervals. The number of particles assigned to each treatment is constant, this uses 30,000 particles per treatment, providing highly resolved treatment plume that computes in a reasonable time frame. For each treatment, chemical mass is specified as total emitted amount per time step. Site specific treatment details are specified in table 12, site details and consented chemical amounts are listed. The Chemical quantity listed for the existing Chalmers Hope Azamethiphos treatment is restricted to 1 treatment of 152 g per day. While Ore Bay was listed in SEPA (2020), no bath treatments are included in the license, therefore this site will not be considered in the cumulative bath treatment analysis.

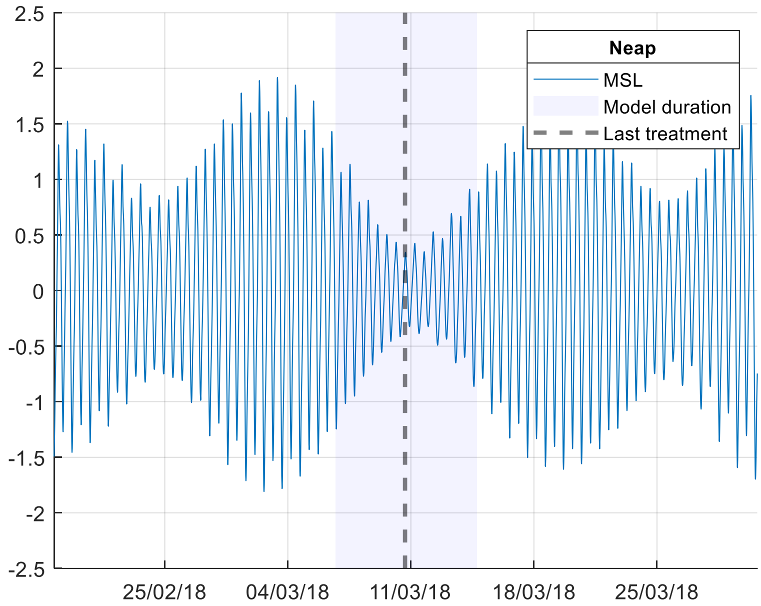
Table 12. Site details for bath treatment model.

	East	North	Pen circumference (m)	Number of Pens	Azamethiphos (grams/ 24hrs)	Deltamethrin (grams/ 3hrs)	Cyphermethrin (grams/ 3hrs)
Brings Head[ǂ]	327370	1002168	80	10	305.5	45.23	120.6
Chalmers Hope[ǂ]	328735	1001311	90	12	152	0	106.4
Chalmers Hope*	328735	1001311	120	12	785	40	16**
Lyrawa Bay	330035	998915	90	8	309.4	9.54	25.43
Pegal Bay	330400	997733	90	8	101.2	8.69	23.18
South Cava	333256	998786	120	16	240.6	17.78	47.41
West Fara	331950	995335	90	12	342	0	94.5
Toyness[ǂ]	335460	1003700	80	10	458.2	20.41	54.44

[ǂ]Existing site information
*Proposed site information
**Mass required to be divided by 267 to achieve compliant consent mass.

The number of treatments per site is restricted to one pen every 3hrs. This provides a maximum of 3 treatments per day. For Azamethiphos, this permits 261.67g to be used for each pen treatment at the proposed Chalmers Hope site. For Deltamethrin and Cypermethrin the chemical consent values provided in table 12 are permitted over a 3hr period and allowing individual pen treatments of the consented amount.

The final treatment of all sites is set to coincide with the maxima of the spring or neap tide that occurred within working hours (08:00-18:00hrs). This is shown for Azamethiphos in figure 7. As wind is omitted from the model there is no requirement to select dates in the summer months. This provides a neap time of 10/03/2018 16:50:00 and a spring time of 03/03/2018 09:50:00. For each bath treatment tested, both spring and neap models are required to pass EQS. The particle tracking model is run for the treatment period, plus an additional 24 hrs to ensure no further ESQ are exceeded.



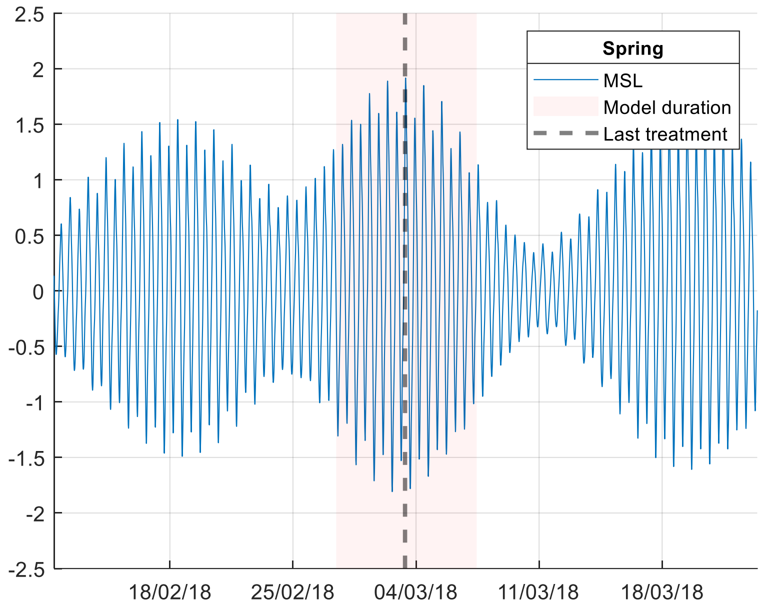


Figure 7. Mean sea level for Neap (top) and Spring (bottom) tides indicating model simulation duration for Azamethiphos with the final treatment from all sites indicated.

3.3.4 Environmental Standards (EQS)

To determine the quantity of chemical used, a hydrodynamic and particle tracking model simulates the chemical release and plume advection. The area coverage and concentration are then monitored to ensure they remain within acceptable tolerances. These environmental quality standards are outlined in SEPA (2021) for Azamethiphos, Cypermethrin and Deltamethrin treatments (table 13). The EQS determines the concentration of the plume area, that must not exceed a site-specific mixing area (A). For the 3- and 6- hour EQS this area is defined as a function of mean current speed (U), time (t) and the horizontal dispersion coefficient (K_X). Mathematically, this is represented as:

$$A = 2\pi \frac{Ut}{2} \sqrt{(2K_x t)}$$

ADCP deployments for Chalmers Hope reveal a mean current speed of 0.133m/s, which gives a 3-hour EQS area of 0.2099km^2 and a 6-hour EQS area of 0.5937km^2. The 72-hour EQS area is not site specific and is assigned a constant value of 0.5km^2.

Additionally, for Azamethiphos a Maximum Allowable Concentration (MAC) is applied. This restricts the peak chemical concentration within the domain after the given time interval. This is not required for Cypermethrin and Deltamethrin.

The 3- and 6- hour EQS restrictions are applied to ensure the short-term compliance of a chemical release. Therefore, these times are referenced to the hours after the chemical discharge of a single, initial treatment event. The 72-hour EQS ensures the long-term compliance of bath chemical use, therefore is applied 72 hours after the final treatment of a full site treatment cycle.

Table 13. Environmental standards for chemical treatments.

	EQS (ng/l)			MAC (ng/l)
	3hrs	6hrs	72hrs	72hrs
Azamethiphos	250	-	40	100
Cypermethrin*	-	16	-	-
Deltamethrin	-	6	-	-
*Quantities of Cypermethrin passing EQS, as shown above, will be reduced by a factor of 267 to comply with SEPA (2018).				

4. Results

4.1 Modelled Flow Fields

The modelled flow dynamics across the west Scapa Flow region during peak spring-neap, flood and ebb tides are shown in figure 8. The flow is constrained and accelerated through the topographical constriction between Graemsay and adjacent coastlines, resulting in two high velocity (>3m/s) jets either side of Graemsay. Velocities also increase, although to a far lesser extent, as the flow is forced around Cava. Flow separation at coastal headlands, bays and the flanks of the tidal jets results in a series of clear recirculation regions associated with lower velocities.

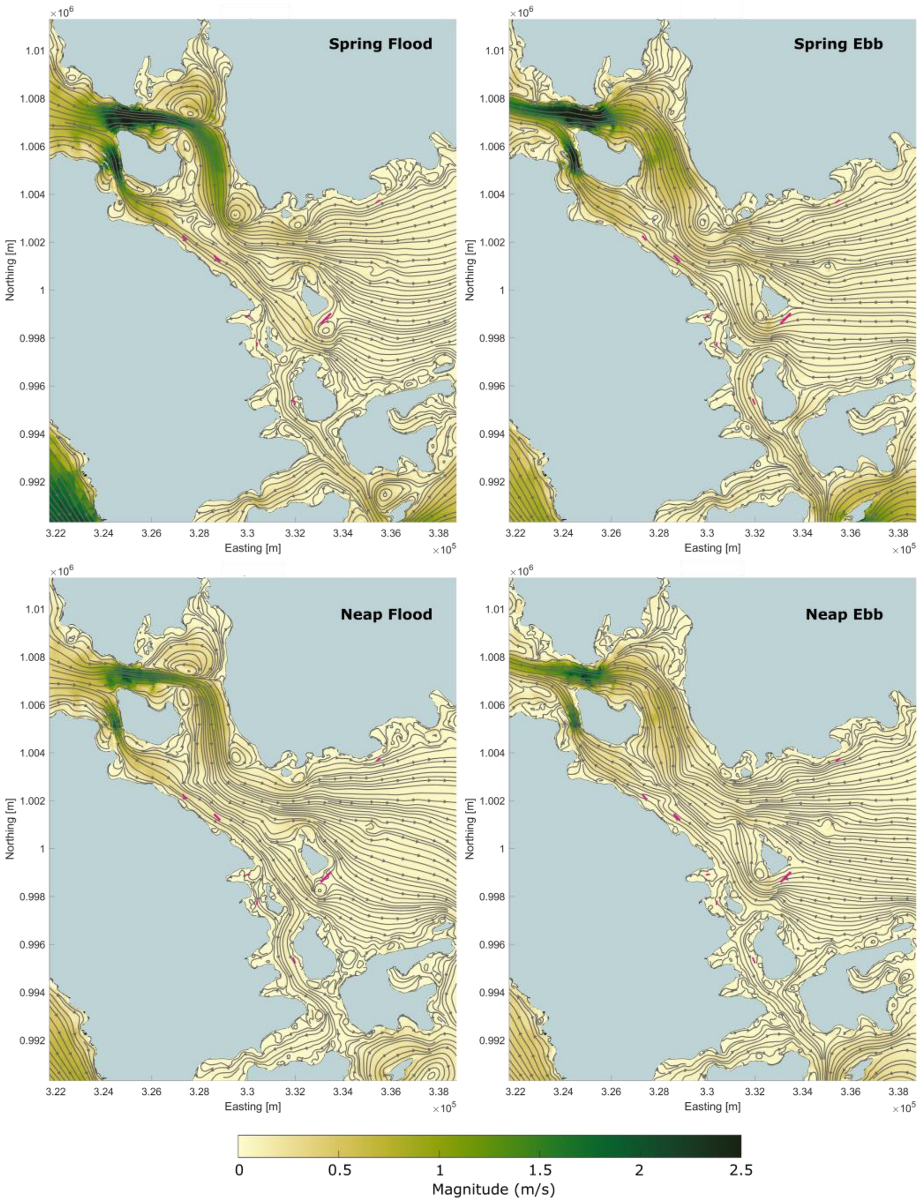


Figure 8 – Modelled flow field across west Scapa flow at peak flooding and ebbing tides for the spring-neap tidal cycle. Grey lines represent flow streamlines and farms are represented by pink rectangles.

At the proposed Chalmers Hope site, a south-easterly flow (~0.2m/s) is observed during the flood tide. This reverses to a north-westerly flow (~0.25m/s) during ebb tides. The large eddies formed at the head of the eastern Graemsay jet during spring tides, self-propagate across Bring Deeps, causing high frequency temporal fluctuation in velocities at the proposed Chalmers Hope site. These features also occur on the neap tide, although they are much smaller and often have little impact on the flow at the site.

4.2 Benthic Particle Tracking

4.2.1 Cumulative Impact

The spatial coverage of depositional solids released from all sites within the west Scapa Flow region is shown in figure 9. The concentrations displayed represent the mean of the final 90 days of the particle tracking model run. Concentration values of less than $1g/m^2$ have been excluded from the map and all subsequent figures. Such low concentrations are not considered to be representative of the main influence of a discharge (SEPA, 2020). Highlighted predicted impact areas are defined as those with deposited concentrations of 250g/m^2 or higher.

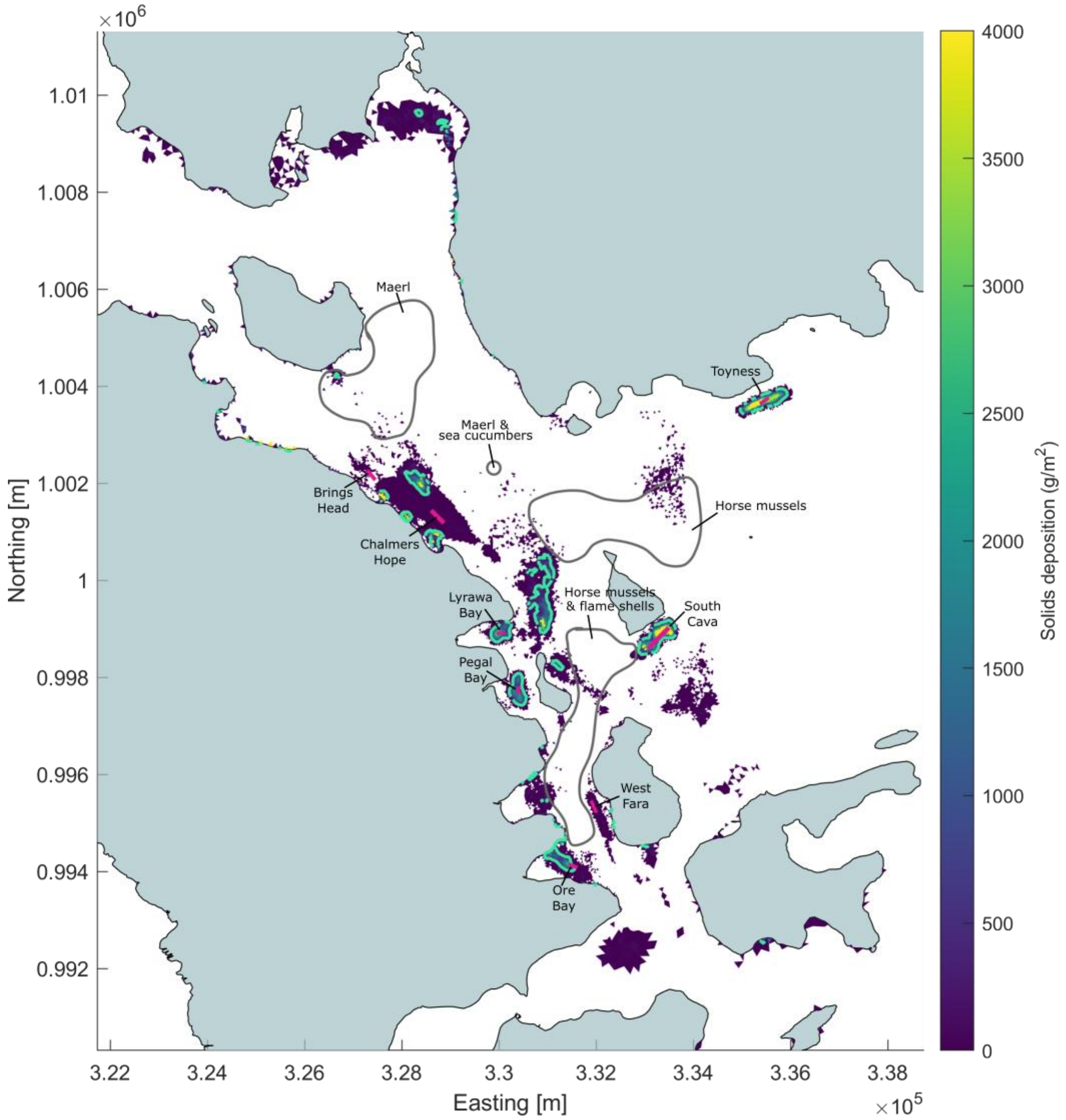


Figure 9 – Mean deposited solids concentration from the proposed Chalmers Hope site and surrounding sites over the final 90 days of the model run period. The location and name of licensed farms (pink rectangles) and sensitive marine features (grey outline) in the region are also shown. The 250g/m^2 contour is shown in light blue.

The far-field benthic modelling results in figure 9, highlight the dispersive nature of the proposed Chalmers Hope site, with only a small accumulation of sediment (mean concentration <50g/m^2) within the 100m mixing zone of the proposed site. As well as this, deposited solids originating from the proposed site can be seen to be transported as far as Clestrain Sound. These further-afield regions of deposition typically consist of far lower concentrations (<10g/m^2) punctuated by a series of smaller impacted (>250g/m^2) pockets.

To determine the influence of the proposed site on the current baseline cumulative impact, the spatial extent of the cumulative impact area with the proposed Chalmers Hope site (2500t) can be compared to the cumulative impact area with the existing Chalmers Hope site (1000t) and to the cumulative impact area with Chalmers Hope omitted entirely. The results of this are shown in table 14. The expansion and repositioning of the Chalmers Hope sites results in a 0.29km^2 increase in the cumulative impacted area. The difference in the impacted area between the proposed site and omitted site indicates that the Chalmers Hope site has a 23.6% contribution to the wider cumulative impact area.

Table 14 - Proposed site influence on cumulative benthic impact.

	Area exceeding 250g/m^2 (km^2)
All sites with proposed Chalmers Hope site	1.78
All sites with existing Chalmers Hope site	1.49
All sites with Chalmers Hope removed	1.36
	Area difference (km^2)
Proposed vs. Existing	0.29
Proposed vs. Removed	0.42
	Percentage difference (%)
Existing vs. Proposed	19.46
Removed vs. Proposed	30.90

The relative contribution of the proposed Chalmers Hope site to the total cumulative solids flux is illustrated in figure 10, as the percentage of the deposited material within the predicted impact areas that originates from the proposed site. For the impact areas in closest proximity to the proposed site, the source of the deposited material is relatively evenly split between Chalmers Hope and neighbouring farm, Bring Head. Similarly, the impacted area within Clestrain Sound originates from both Brings Head and Chalmers Hope, with each site contributing 30% and 70%, respectively. The largest area of impact is predicted between the east coast of Hoy and west coast of Cava. The proposed Chalmers Hope site is the predominant contributor to the northern portion of this area, whereas South Cava is the primary source of sediment for the southern portion.

The Chalmers Hope Screening modelling and risk identification report by SEPA (2020) highlighted the vulnerability of Lyrawa Bay and Pegal Bay sites to the sediment influence from the proposed Chalmers site as a potential risk of the development. However, as can be seen from figure 10 Chalmers Hope does not contribute any material to the impacted areas associated with the Lyrawa and Pegal Bay farms.

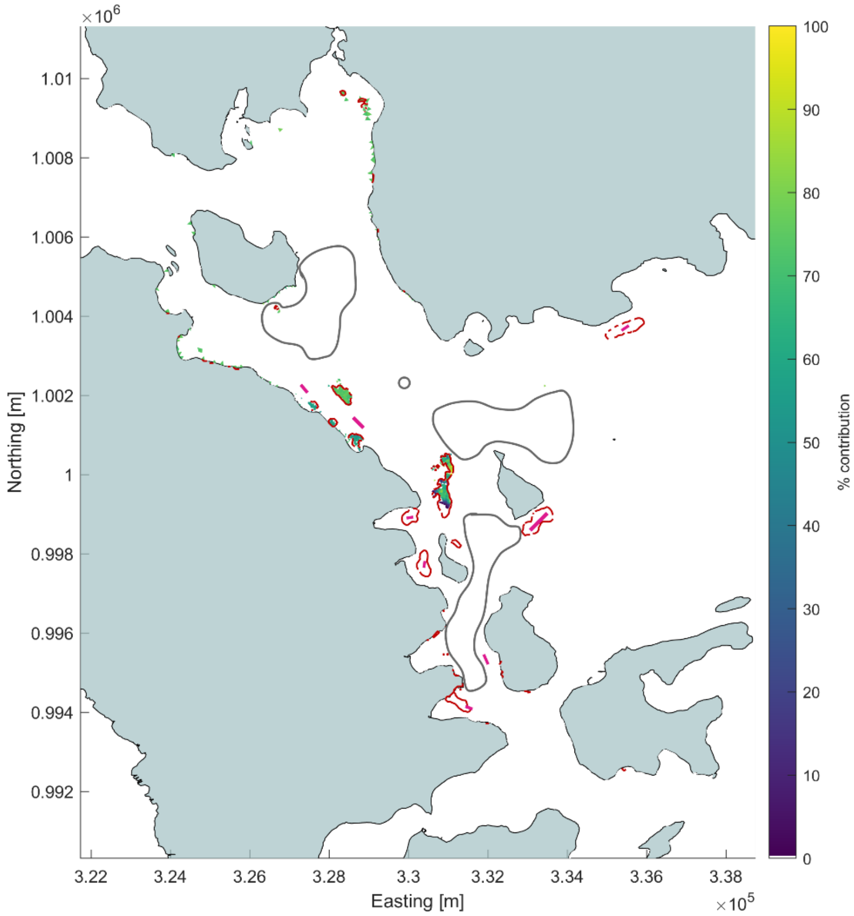


Figure 10 – Percentage contribution of deposition originating from the proposed Chalmers Hope site towards cumulative predicted areas of impact. The $250g/m^2$ contour is shown in red.

4.2.2 PMF Impact

Timeseries of the percentage area within each sensitive marine feature that exceeds the EQS intensity threshold of $250g/m^2$ are shown in figure 11. When considering the release of particulate waste from all sites within the west Scapa flow domain, less than 0.1% of all PMFs, identified in the Chalmers Hope Screening modelling and risk identification report by SEPA (2020), were impacted. Therefore, suggesting the cumulative effects or risk to these sensitive regions is very small. This is further supported by figure 9, which shows almost no deposition occurring within the sensitive marine features. Scattered low concentrations ($<5g/m^2$) are predicted across parts of the Horse Mussel beds to the north and south of Cava, indicating no significant benthic impact in these areas. Within the Maerl bed, near the south-eastern coast of Graemsay, a region of impacted seabed is predicted, however the area effected is small, less than $0.009km^2$.

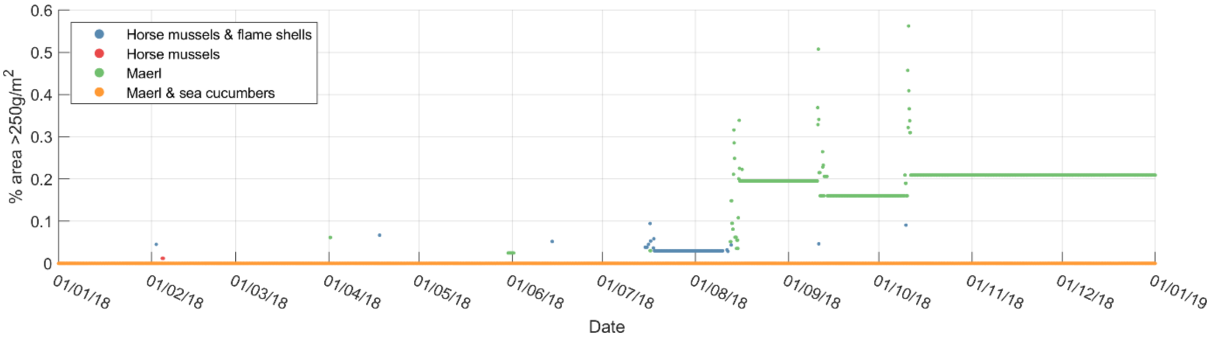


Figure 11 – Model run timeseries of the percentage area of the sensitive marine features that exceeds the EQS threshold. The locations of the PMFs are shown in figure 9.

4.2.4 EQS Compliance

To explore how the cumulative far-field benthic modelled results compare with EQS compliance, a collective 100m mixing zone area is calculated by summing the 100m mixing zone areas of the eight individual sites considered here. This produces a combined west Scapa Flow 100m mixing zone area of 1.03km^2. The predicted impact area of deposition from all sites, defined as regions enclosed by the 250g/m^2 contour corresponding to an equivalent IQI of 0.64, is 1.78 km^2 (figure 12). This is equivalent to 172.4% of the combined 100m mixing area, or 0.68% of the Scapa Flow waterbody area, defined by the Water Framework Directive as 263.3 km^2 (SEPA, 2007). A predicted mean deposition of 1605.6 g/m^2 occurs across the predicted impact areas.

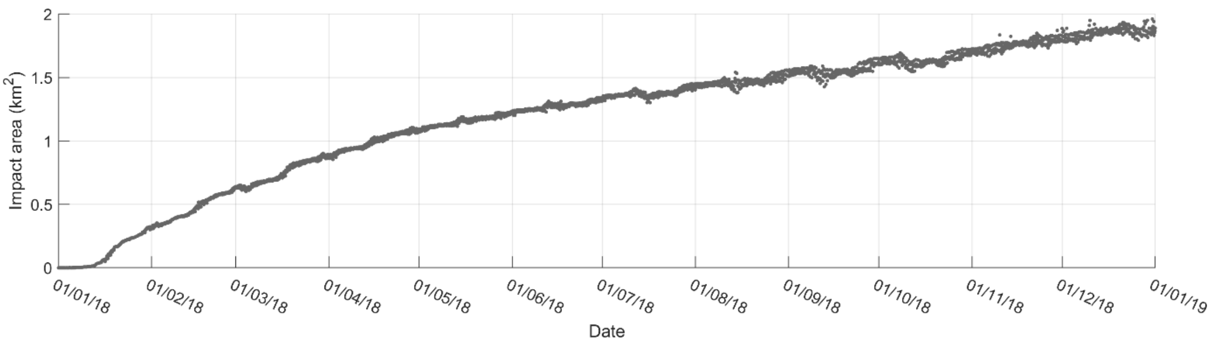


Figure 12– Model run timeseries of impact area (>250g/m^2) spatial extent from the proposed Chalmers Hope site and surrounding sites.

The intensity of the predicted cumulative benthic deposition for all sites is below the EQS level of 2000g/m^2. However, the spatial extent of the predicted impact is above the threshold EQS parameter of 100% of the 100m mixing zone area.

4.2.5 Discussion

The findings of the far-field benthic modelling campaign address the concerns regarding marine priority features and cumulative farm effects, highlighted in the Chalmers Hope screening modelling and risk identification report by SEPA (2020). The benthic model setup has purposely been tailored to replicate a worst-case scenario and generate the most severe environmental impacts. All farms within west Scapa Flow are assumed to be operating at maximum biomass for the entire model run period. No decay or breakdown of particles occur within the model, dispersive processes are limited due to the use of a conservative vertical and horizontal dispersion coefficients and vertical variability in velocity experienced by particles is not considered.

The amount of waste feed and faeces produced directly scales with the biomass at a site. Modelling farms at maximum biomass means a greater mass of waste organic particles are released in the model, resulting in larger and higher concentration impacted areas. In reality, individual farm biomass would be below the maximum consented amount for a considerable proportion of the year. Also, due to stocking logistics it is highly unlikely that the periods of maximum biomass would coincide between different farms, meaning less waste organic particles would be released into the model under more realistic farm operating procedures.

The horizontal and vertical dispersion coefficients were set to the default values of 0.1m^2/s and 0.001m^2/s, respectively. This limits the random, turbulent processes that drive non-advective mixing within the model. In reality, both dispersion coefficients vary through time and space, driven by a host of factors such as weather conditions, stratification and tidal state. It was observed during the dye and drogue study that high winds likely act as the predominant driver for horizontal particle dispersal at the proposed site. Given fish are fed daily and faeces is produced continuously, waste particles will frequently be released from a site in more dispersive conditions than modelled, resulting in a greater spread and lower concentrations of deposited waste.

No decay or degradation of organic particles was included in the benthic model. In the natural environment organic particles are scavenged and/or broken down through microbial processes as they sink through the water column and/or when settled on the seabed. These processes would act to remove a proportion of the modelled particles from the domain, resulting in reduced accumulation at the seabed.

The benthic particle tracking model is forced by depth-averaged flows derived from a 2D hydrodynamic model. Therefore, the effect of vertical flow features - which are assumed to be common in the complex west Scapa Flow domain - on the resuspension and transportation of organic waste is not captured in the model. To accurately resolve three-dimensional flow variability, a three-dimensional hydrodynamic model is required, dramatically increasing the computational resource needed.

The results show, under these worst-case assumptions, the proposed Chalmers Hope site provides a small contribution to overall cumulative benthic impact area. The dispersive nature of the site transports waste feed and faeces over a large area, this primarily is shown not to settle within PMF areas, therefore, even when considering a very conservative approach the new site performs well.

4.3 Bath Treatment Particle Tracking

The simulation of bath treatments from all sites within west Scapa Flow was considered. This models the release of Azamethiphos, Cypermethrin and Deltamethrin and the dilution of the chemical plume in relation to the relative EQS, these results are provided in table 15. This indicates compliance is achieved with all proposed chemical treatments. A detailed description for each chemical treatment is presented in section 4.3.1 to 4.3.3

Table 15. Environmental standards for MAC and area EQS for all treatments.

	Treatment Quantity (grams)	MAC 72 hrs (µg/l)	EQS 3hrs (km^2)	EQS 6hrs (km^2)	EQS 72hrs (km^2)
Azamethiphos					
Neap					
3hr	466.67	-	0.054 (25.7%)	-	-
72hr	261.67	0.073 (72.7%)	-	-	0.44 (88.3%)
Spring					
3hr	466.67	-	0.065 (31.2%)	-	-
72hr	261.67	0.029 (29.1%)	-	-	0 (0%)
Cypermethrin					
Neap					
6hr	16	-	-	0.122 (20.5%)	-
Spring					
6hr	16	-	-	0.14 (24.1%)	
Deltamethrin					
Neap					
6hr	40	-	-	0.14 (23.6%)	-
Spring					
6hr	40	-	-	0.31 (52.1%)	-

4.3.1 Azamethiphos

Compliance was achieved at the proposed Chalmers Hope site using 466.67 g of Azamethiphos within for a 3hr single treatment or 785g in a 24hr period. This equates to an individual treatment mass of 261.67 g per pen, assuming 3 treatments per day with a 3-hour interval.

4.3.1.1 Neap Tides

The dispersal of Azamethiphos is calculated for a neap tidal phase. The particle tracking model is initiated on 05/03/2018 16:00:00 and ends on 14/03/2018 17:50:00. The last treatment is administered for all sites on 10/03/2018 16:00:00, corresponding to the maxima of the neap tidal cycle, where the final treatment is released at highwater.

To assess the short-term compliance for Azamethiphos, a single tarpaulin release of a 3-hour mass (466.67g) is modelled. The size of the 3-hour EQS plume following this initial release (0 hours on the x axis) is shown in figure 12. The size of the chemical plume after a single treatment remains less than the calculated mixing area of 0.2099km^2, peaking at 0.2098km^2 after 25 hours the initial release. The 3hr EQS time has an area of 0.054km^2, equivalent to 25.7% of the EQS area.

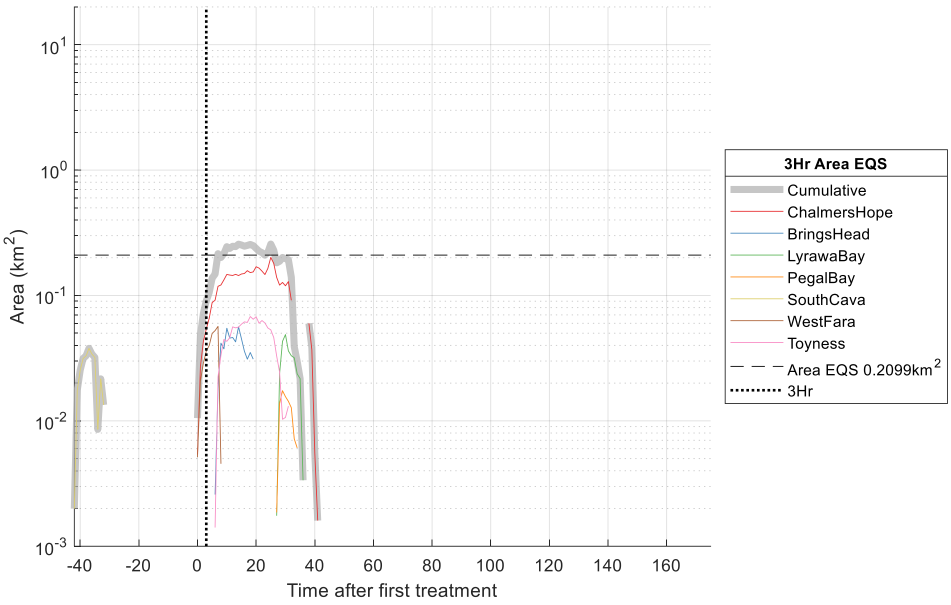


Figure 12. Neap tide area exceeding 3hr EQS value (250 ng/l) for all sites.

To assess the long-term risks from Azamethiphos, the full treatment regime is modelled. This simulated an individual treatment mass of 261.67g, resulting in a maximum 24hr treatment mass of 785g. The MAC for the neap tidal cycle is plotted in figure 13. 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. At 72 hours after the final treatment the concentration from the proposed Chalmers Hope site is 0.073 µg/l, this is 72.7% of the EQS value. Following this a general decline in MAC is observed.

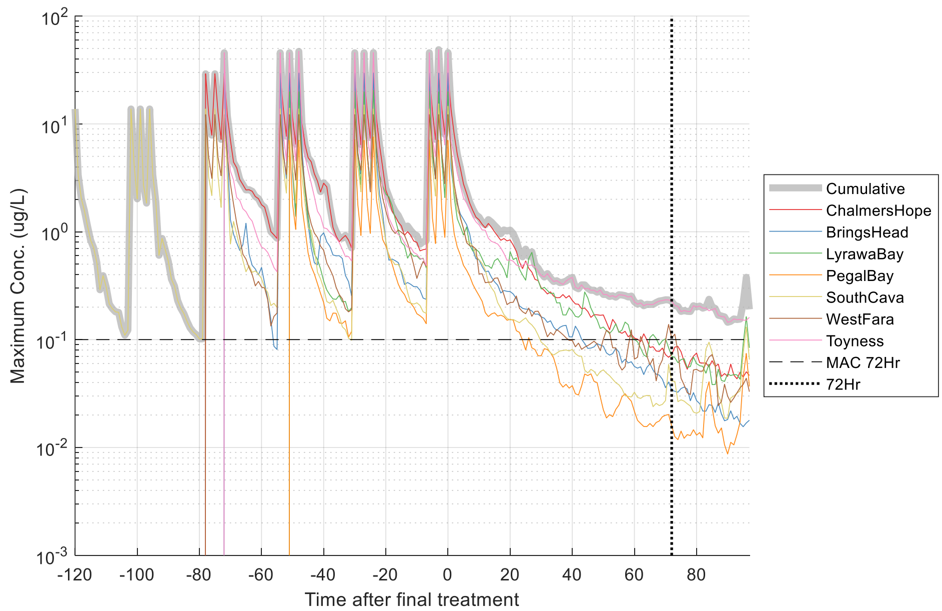


Figure 13. Maximum concentration of Azamethiphos during neap tide release. Cumulative impact plotted as solid grey line and MAC for the 72 hour EQS (100 ng/l) is indicated by grey dotted line.

The area of the chemical plume exceeding 40ng/l (72-hour EQS) is plotted in figure 14. At 72 hours after the final treatment, the size of the chemical plume decreases rapidly, meaning at the 72-hour EQS time the area exceeding 40 ng/l is 0.44 km^2, this is 88.3% of the 0.5 km^2 EQS area.

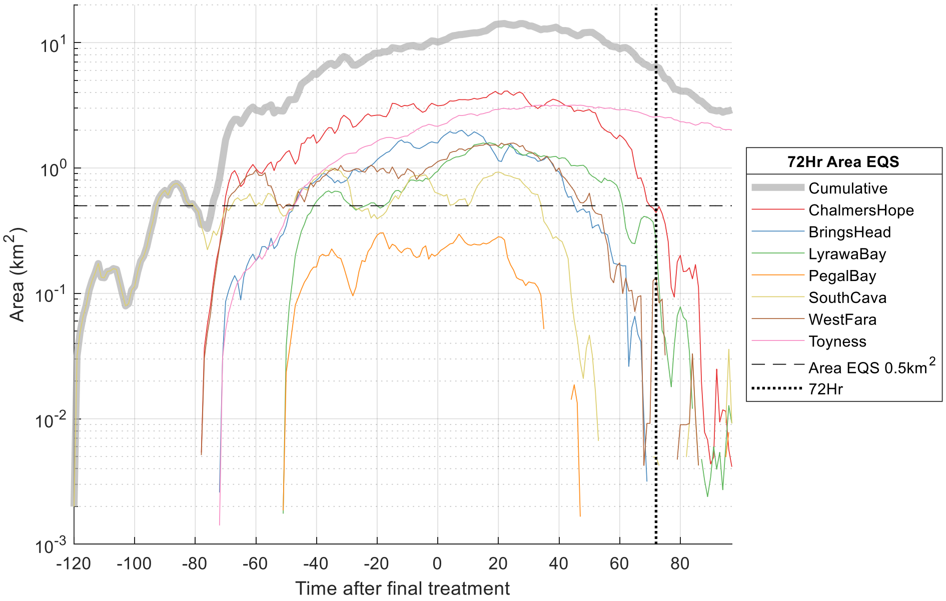


Figure 14. Neap tide area exceeding 72hr EQS value (40 ng/l) for all sites.

The spatial distribution of Azamethiphos during the simultaneous release of bath treatments during neap tides are shown in figure 15. This indicates the area extent using gold contour lines where concentrations exceed the relevant EQS value. The 3hr EQS indicates multiple small patches near each farm location. While the cumulative area exceeds the 0.5km^2, this remains a small proportion of the area of the waterbody. The 72hr EQS shows a more developed distribution of treatments with combined treatments located further from farm locations. When the spatial plot is compared with the area EQS plot above (figure 14), the large cumulative area coverage can be disentangled, showing that Chalmers Hope only provides a small contribution towards the overall area at the EQS time.

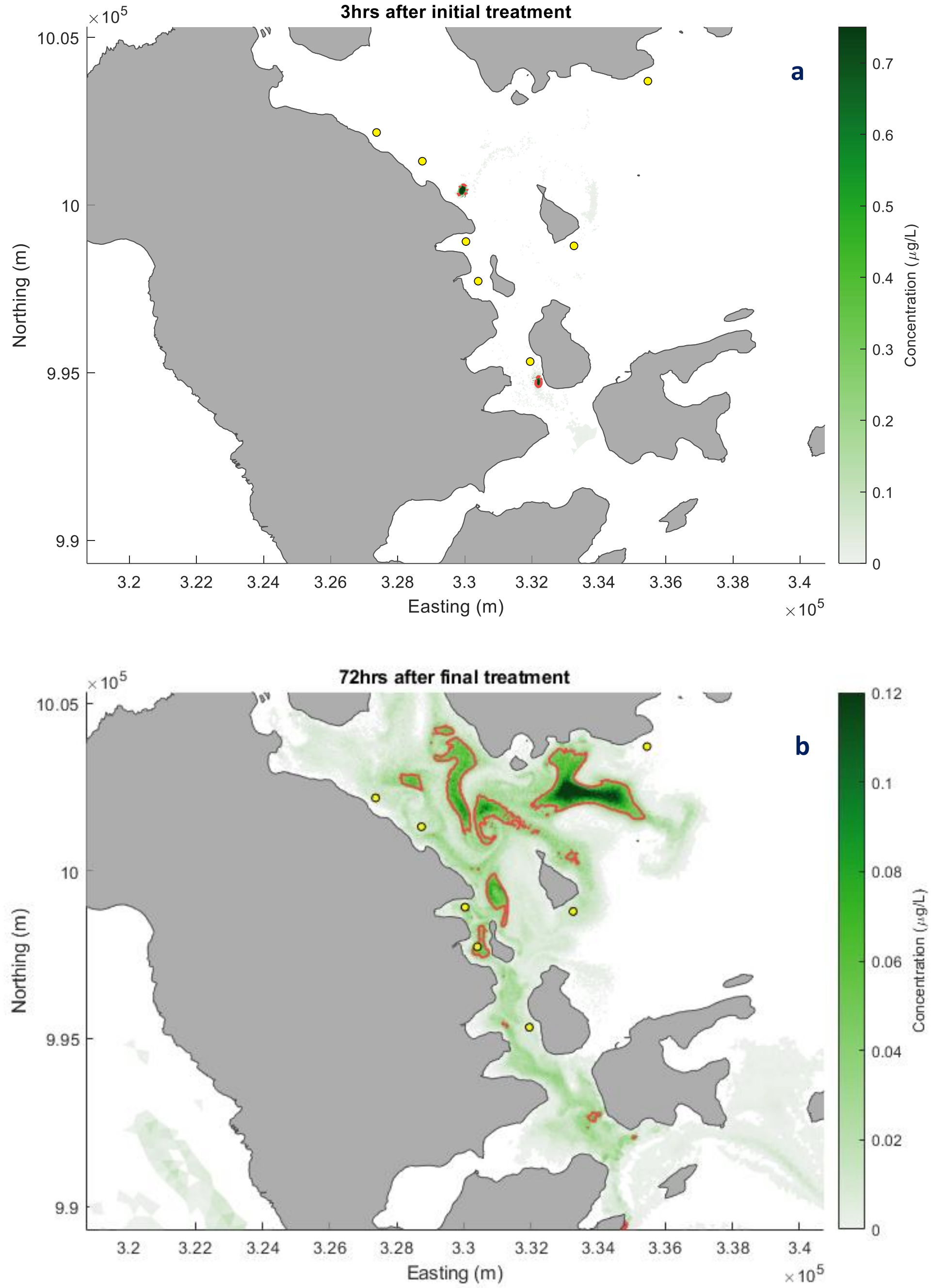


Figure 15. Spatial Azamethiphos distribution for tarpaulin release during neap tides 3hr after the initial 3-hour mass release (a) and 72hr after the last treatment event (b). Areas above EQS values are indicated within the red contour and site locations are identified using a yellow marker.

4.3.1.2 Spring Tides

The dispersal of Azamethiphos is calculated for a spring tidal phase. The particle tracking model is initiated on 26/02/2018 09:00:00 and ends on 07/03/2018 10:50:00. The last treatment is administered for all sites on 03/03/2018 09:00:00, corresponding to the maxima of the spring tidal cycle, where the final treatment is released at highwater.

To assess the short-term compliance for Azamethiphos, a single tarpaulin release of a 3-hour mass (466.67g) is modelled. The size of the 3-hour EQS plume following this initial release (0 hours on the x axis) is shown in figure 16. The size of the chemical plume after a single treatment remains less than the calculated mixing area of 0.2099km^2, peaking at 0.186km^2 after 17 hours the initial release. The 3hr EQS time has an area of 0.065km^2, equivalent to 31.2% of the EQS area.

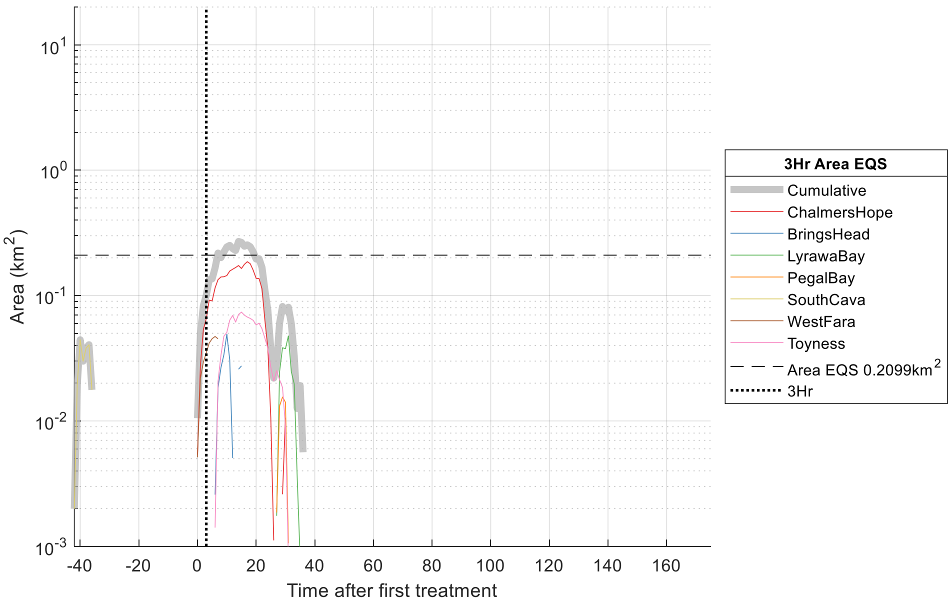


Figure 16. Spring tide area exceeding 3hr EQS value (250 ng/l) for all sites.

To assess the long-term risks from Azamethiphos, the full treatment regime is modelled. This simulated an individual treatment mass of 261.67g, resulting in a maximum 24hr treatment mass of 785g. The MAC for the spring tidal cycle is plotted in figure 17. Again, 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. At 72 hours after the final treatment the concentration from the proposed Chalmers Hope site is 0.029 µg/l, this is 29.1% of the EQS value. Following this a general decline in MAC is observed.

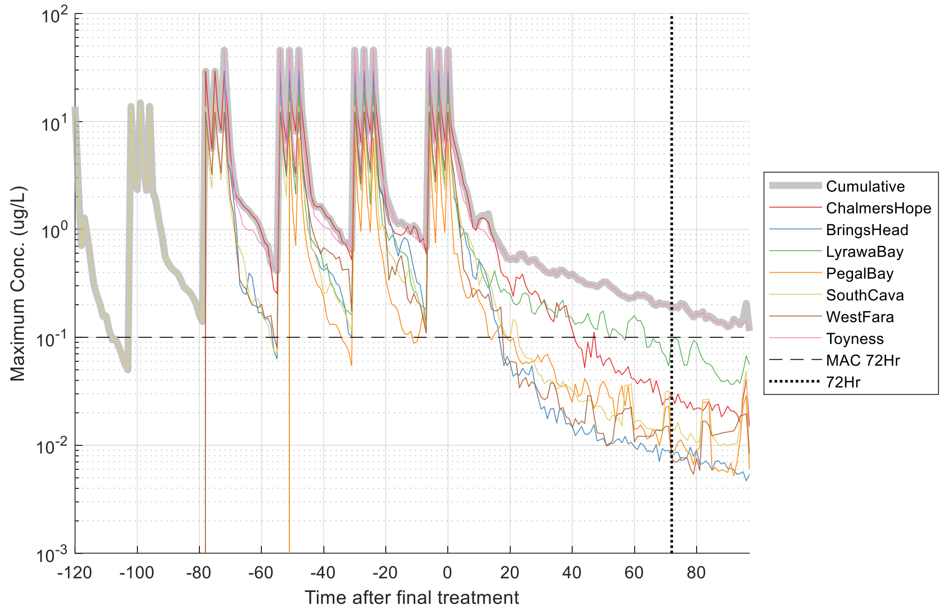


Figure 17. Maximum concentration of Azamethiphos during spring tide release. Cumulative impact plotted as solid grey line and MAC for the 72 hour EQS (100 ng/l) is indicated by grey dotted line.

The area exceeding the 72-hour EQS concentration (40ng/l) is plotted in figure 18. The greater mixing capability of spring tides is captured, where after ~60 hours no chemical plumes with a concentration exceeding 40ng/l exist.

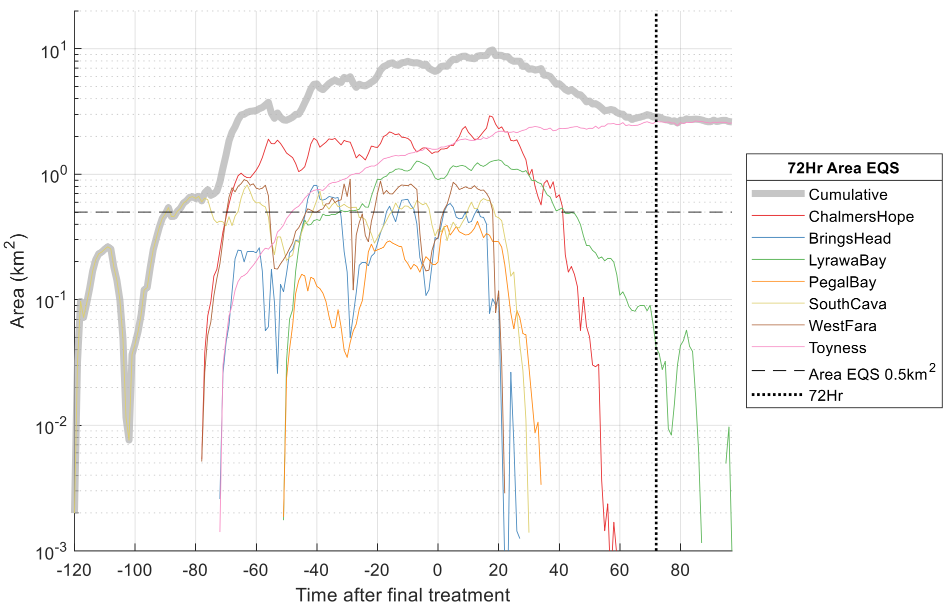


Figure 18. Spring tide area exceeding 72hr EQS value (40 ng/l) for all sites.

The spatial distribution of Azamethiphos treatments during spring tides is shown in figure 19. The 3hr time interval shows smaller area coverage above the EQS value when compared to the neap tide. These areas are transient but have not yet had time to leave the vicinity of their initial treatment site. By 72hr, the majority of bath treatment plumes have dispersed below the EQS threshold. For most sites, no further EQS area is recorded.

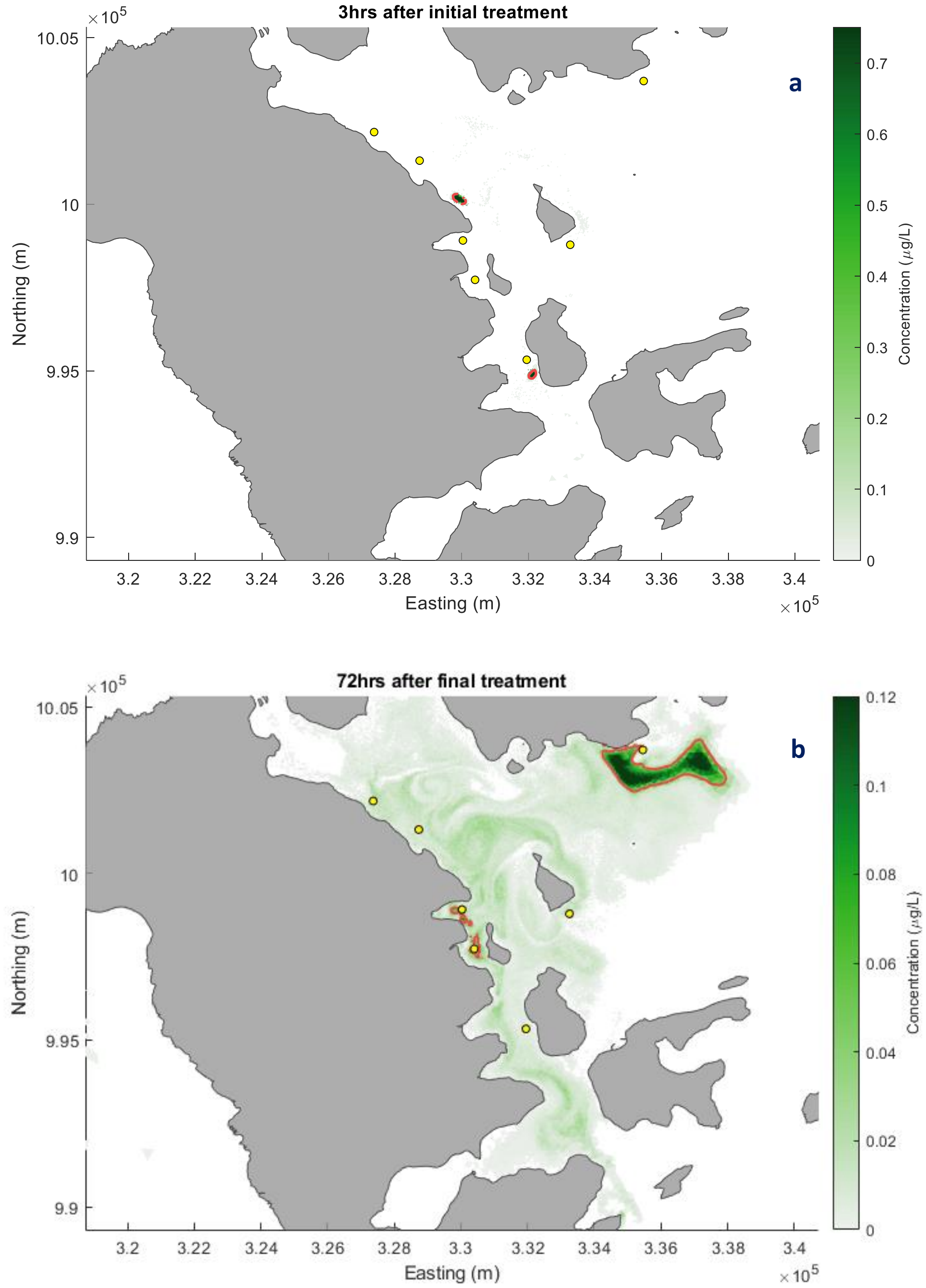


Figure 19. Spatial Azamethiphos distribution for tarpaulin release during spring tides 3hr after the initial 3-hour mass release (a) and 72hr after the last treatment event (b). Areas above EQS values are indicated within the red contour and site locations are identified using a yellow marker.

4.3.1.3 Cumulative Assessment

To determine the influence of the proposed site on the presented cumulative impact, two additional cases were simulated. This considered the chemical release from the existing site and a zero-baseline, where the Chalmers Hope site was completely removed. The results quantify the area impact at the EQS times, indicating any change to the existing or zero-baseline area. The results are shown in table 16. Due to the increased chemical quantity specified, the proposed site is shown to have a larger cumulative chemical footprint than the existing or zero-baseline. Tidal phase and EQS time are also shown to affect the plume area. The 3hr EQS does not permit much time for chemical plumes to develop and propagate, this essentially allows combined effects to be calculated by summing individual site areas. The 72 hr EQS provides a reasonable time frame for plumes to disperse and merge with each other, providing a more complicated spatial distribution. During neap tides the 72hr proposed cumulative area increases by 3.73 km^2, relative to the existing site's treatment plan. Spring tides indicate much lower area differences, where contributions to the cumulative impact are much smaller. During these periods, the proposed cumulative area increase is calculated at 0.69km^2 relative to the existing site's treatment plan.

Table 16. Proposed site influence on cumulative impact.

	3hr EQS		72hr EQS	
	Neap	Spring	Neap	Spring
	All Sites - Area exceeding EQS threshold (km^2)			
All sites (Proposed) (km^2)	0.03	0.03	6.45	2.88
All sites (Existing) - (km^2)	0.09	0.02	2.72	2.19
Chalmers Hope site removed (km^2)	0.03	0.03	3.74	2.74
	Area difference (km^2)			
Proposed vs. Existing	-0.06	0.01	3.73	0.69
Proposed vs. Removed	0	0.18	2.71	0.14
	Percentage difference (%)			
Proposed vs. Existing	-200	33.33	57.83	23.95
Proposed vs. Removed	0	0	42.08	5.00

The single treatment of 466.67g of Azamethiphos is shown to be compliant with the 3hr short duration EQS. The repeat treatment of 261.67g of Azamethiphos per pen with a 3hr treatment interval is shown to be compliant with all longer duration MAC and EQS. Cumulative modelling of all treatments within the area shows that as the treatment schedule finishes, the plumes released from Chalmers Hope are very quickly dispersed, resulting in no or minor contribution to any cumulative EQS exceedance. Furthermore, any prolonged EQS exceedance observed within the model occurs from other sites and is unrelated to the proposed treatment at Chalmers Hope.

The simulated treatment quantity provides a recommended consent mass of 466.67g per 3 hours and 785g per 24 hours. This provides a treatable volume of 2616.7 m^3 with a concentration of 100000 ng/l. This volume is sufficient to treat 0.77 cone-shaped pens per 3 hours or 1.74 wellboat treatments (1,500m^3 capacity). The depth of the cone-shaped pen is calculated by applying a 25° net angle from the circumference of the pen.

4.3.2 Cypermethrin

Environmental compliance was achieved at the proposed Chalmers Hope site using 16g of Cypermethrin within a 3hr period. For the 6hr EQS period, this permits two releases resulting in a total treatment quantity of 32g. A reduction factor of 267 is applied to the compliant chemical quantity to achieve the actual consent mass. This provides a recommended consent mass of 0.059925g (3hr) or 0.11985g (6hr). This provides a 3hr treatment volume of 12.7 m^3

4.3.2.1 Neap tides

The dispersal of Cypermethrin is calculated for a neap tidal phase. The particle tracking model is initiated on 10/03/2018 05:20:00 and ends on 12/03/2018 15:20:00. The first treatment is administered for all sites on 11/03/2018 05:20:00, corresponding to the lowest high-water event within the spring/neap cycle.

The MAC for the neap tidal cycle is plotted in figure 20. The individual pen treatments are identified by the colour coded site-specific spikes. Chalmers Hope is shown to have peak concentration values much lower than the surrounding sites. After each treatment chemical plumes are dispersed, and maximum concentration values fall rapidly. No MAC environmental standard exists for the use of Cypermethrin.

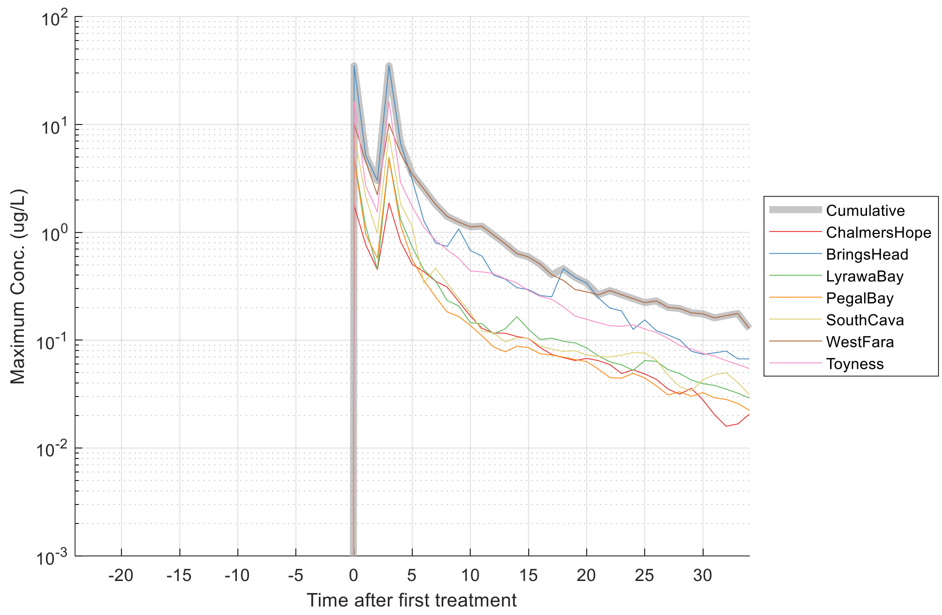


Figure 20. Maximum concentration of Cyphermethrin during neap tide release. Cumulative MAC is indicated by grey solid line

The area exceeding the 6hr EQS value is plotted in figure 21. This shows that the chemical plume from Chalmers Hope remains below 0.59 km^2 with a concentration of 16ng/l. Cumulative treatments show a large combined area, where Chalmers Hope has a minimal contribution.

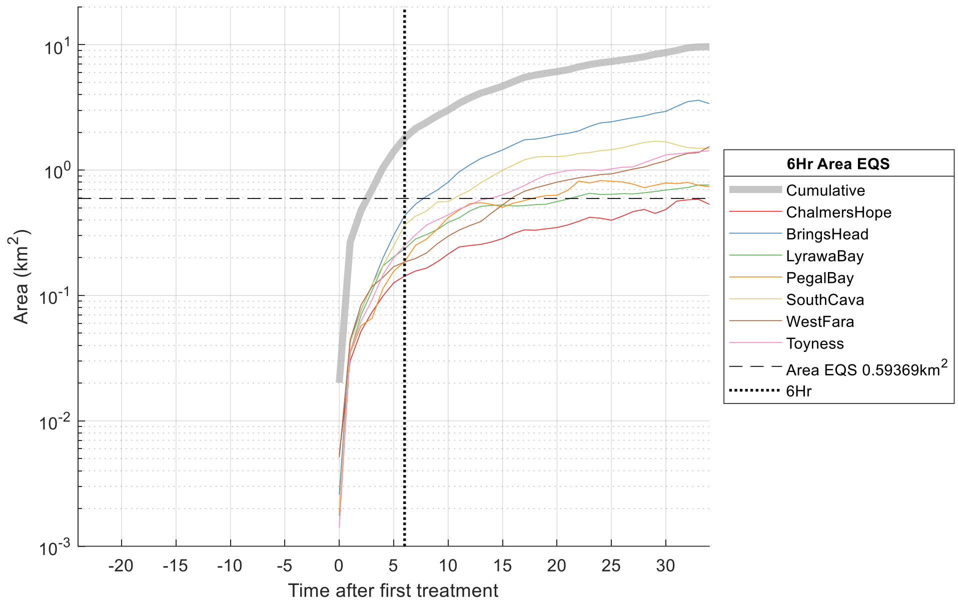


Figure 21. Cypermethrin neap tide area exceeding 6hr EQS value (16 ng/l) for all sites.

The spatial distribution of Cyphermethrin after simultaneous release of bath treatments from all sites during a neap tide is shown in figure 22. This indicates the area extent using red contour lines where concentrations exceed time dependent thresholds. The 6hr EQS area identifies small plumes leaving all sites as the initial treatment is administer. Due to the relatively short time frame and lower neap current speeds, no plumes overlaps occur.

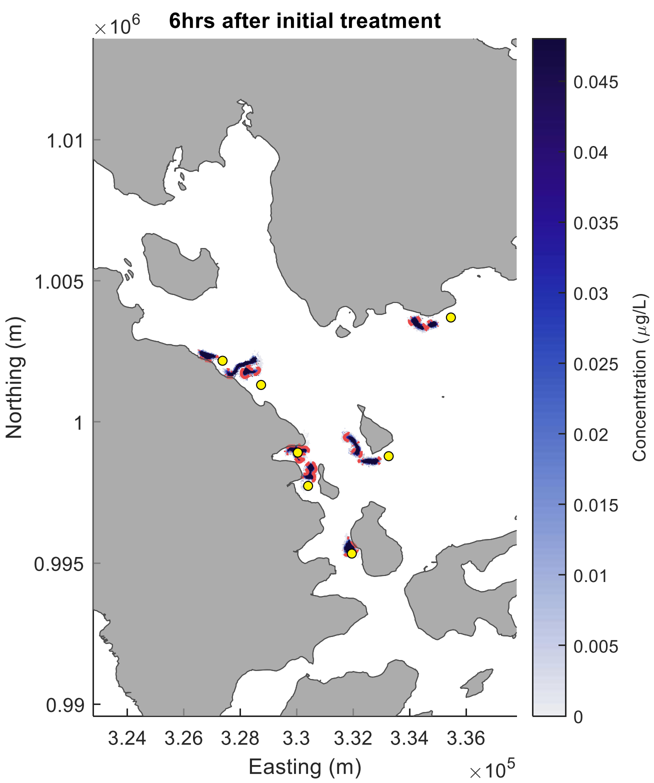


Figure 22. Spatial Cypermethrin distribution following tarpaulin releases during neap tides 6hr after the last treatment event. Areas above EQS values are indicated within the red contour and site locations are identified using a yellow marker.

4.3.2.2 Spring tides

The dispersal of Cypermethrin is calculated for a spring tidal phase. The particle tracking model is started on the 02/03/2018 09:50:00 and finishes on 04/03/2018 19:50:00. The first treatment is administered for all sites on the 03/03/2018 09:50:00. This corresponds to the largest high-water event within the spring/neap cycle.

The MAC for the spring tidal cycle is plotted in figure 23. Chalmers Hope shows low concentrations resulting in quick dispersal to very low concentrations.

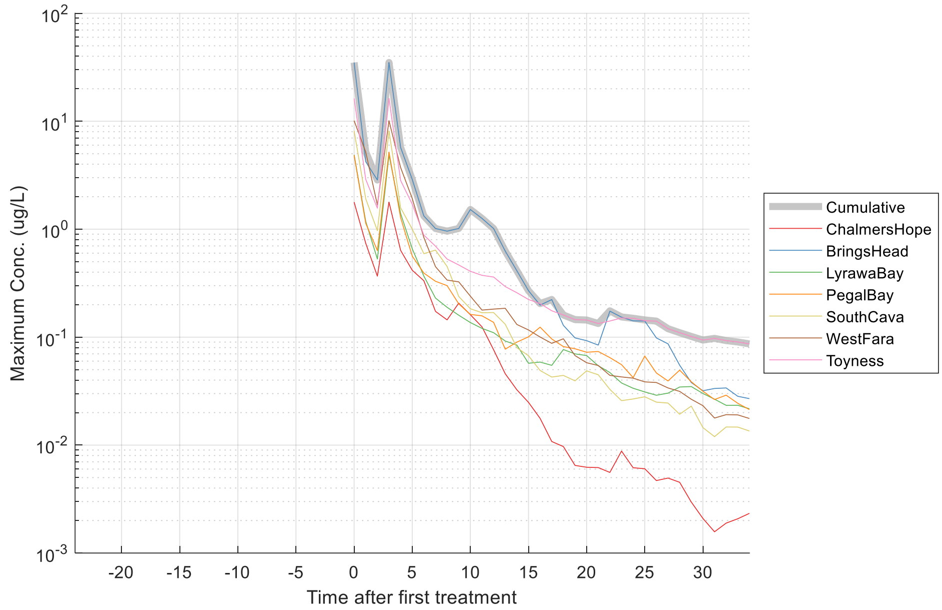


Figure 23. Maximum concentration of Cyphermethrin during spring tide release. Cumulative MAC is indicated by grey solid line.

The area exceeding the 6hr EQS value is plotted for the spring tide, this is shown in figure 24. After the second treatment, Chalmers Hope shows very low plume area exceeding 16ng/l, where at 25 hrs no values exceed the EQS threshold. The cumulative results for the region show much greater area coverage, however, the discharge from Chalmers Hope provides a minimum contribution to the overall area exceeding the area of the EQS threshold.

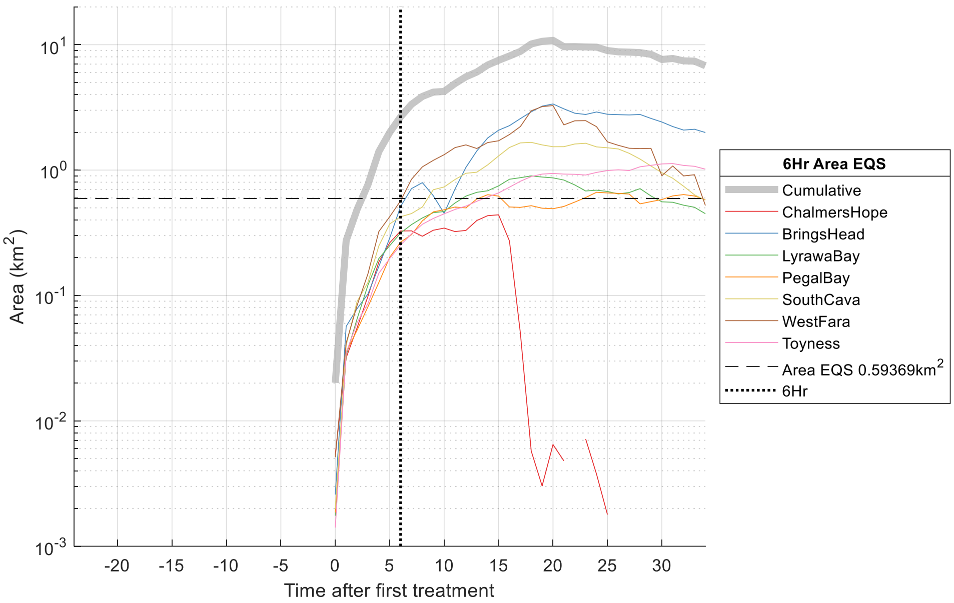


Figure 24. Cypermethrin spring tide area exceeding 6hr EQS value (16 ng/l) for all sites.

The spatial distribution of Cyphermethrin 6hrs after the first treatment from all sites during a spring tide is shown in figure 25. The 6hr EQS area identifies a dynamic distribution of chemical plumes, where plumes are elongated with larger areas of lower concentrations when compared to the neap tides. The chemical plumes are entrained by local eddies and transported further within Scapa Flow.

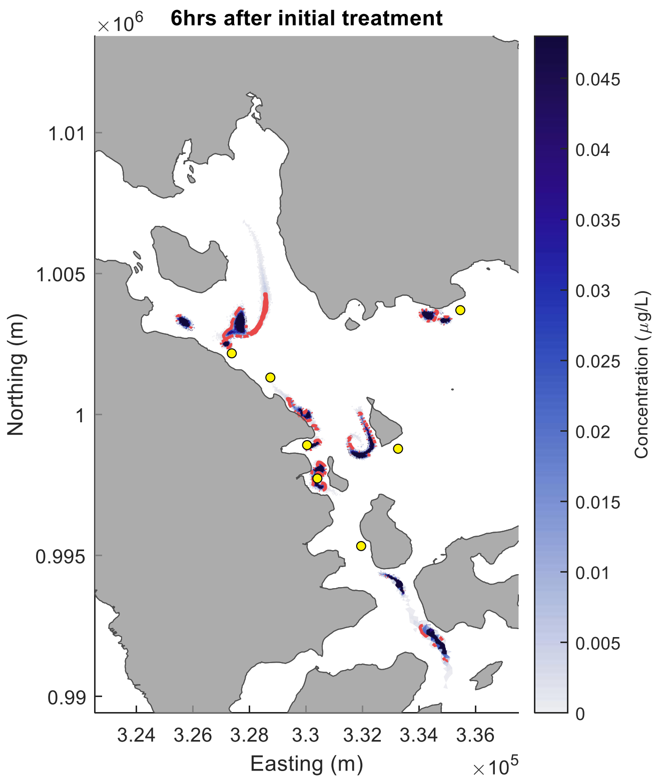


Figure 25. Spatial Cypermethrin distribution following tarpaulin releases during spring tides 6hr after the last treatment event. Areas above EQS values are indicated within the red contour and site locations are identified using a yellow marker.

4.3.2.3 Cumulative assessment

To determine the contribution of the proposed site on the presented cumulative impact, the existing site and a zero-baseline, where the Chalmers Hope site was completely removed, were simulated and compared. The results quantify the area impact at the EQS times, indicating any change to the existing or zero-baseline area. The results are shown in table 17. Due to the large chemical quantity specified at the existing site, the proposed site is shown to have a lower cumulative chemical footprint. This has an area difference of -0.09 and -0.48 km^2, for the respective neap and spring tides.

Table 17. Proposed site influence on cumulative impact.

	6hr EQS	
	Neap	Spring
	All Sites - Area exceeding EQS threshold (km^2)	
All sites (Proposed) (km^2)	1.80	2.66
All sites (Existing) - (km^2)	1.89	3.14
Chalmers Hope site removed (km^2)	1.65	2.34
	Area difference (km^2)	
Proposed vs. Existing	-0.09	-0.48
Proposed vs. Removed	0.14	0.32
	Percentage difference (%)	
Proposed vs. Existing	-5.00	-18.05
Proposed vs. Removed	7.95	12.02

The treatment of 16 g of Cyphermethrin per pen with a 3hr interval is shown to be compliant with all EQS. Cumulative modelling of all treatments within the area shows small chemical distributions from all farms being very dispersed.

The simulated treatment quantity provides a mass of 16 g. To obtain the recommended consent mass this must be reduced by a factor of 267 to compile with (SEPA 2018). This provides a recommended consent mass of 0.059925 g. This provides a treatment volume of 11.99 m^3, with a treatment concentration of 5,000 ng/l. This can treat 0.0004 reduced (cone) depth pen treatment or 0.008 1,500 m^3 wellboat treatments.

4.3.3 Deltamethrin

Compliance was achieved at the proposed Chalmers Hope site using 40g of Deltamethrin within a 3hr period. For the 6hr EQS period, this permits two releases resulting in a total treatment quantity of 80g. This provides a recommended consent mass of 40g (3hr) or 80g (6hr). This provides a 3hr treatment volume of 20,000 m^3.

4.3.3.1 Neap tides

The dispersal of Deltamethrin is calculated for a neap tidal phase. The particle tracking model is started on 10/03/2018 05:20:00 and finishes on 12/03/2018 15:20:00. The first treatment is administered for all sites on 11/03/2018 05:20:00, corresponding to the lowest high-water event within the spring/neap cycle.

The MAC for the neap tidal cycle is plotted in figure 26. The individual pen treatments are identified by the colour coded site-specific spikes. Chalmers Hope shows large initial concentrations, that quickly reduces as plumes disperse. No MAC environmental standards are applied to Deltamethrin.

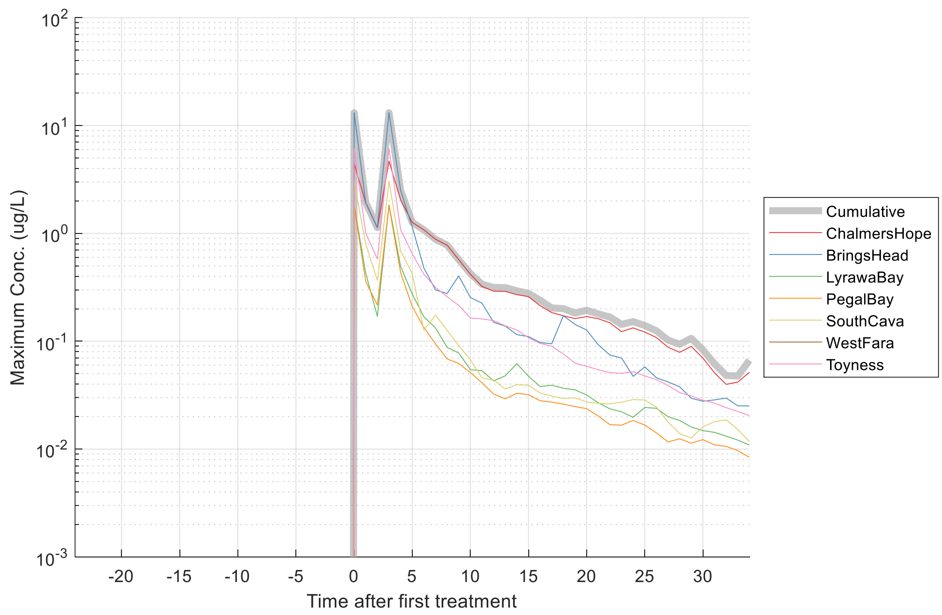


Figure 26. Maximum concentration of Deltamethrin during neap tide release. Cumulative MAC is indicated by grey solid line.

The area exceeding the 6hr EQS value is plotted in figure 27. This shows that the chemical plume from Chalmers Hope always remains below 0.59 km^2 with a concentration of 6ng/l. The 6hr EQS time has an area of 0.14 km^2, equivalent to 23.6% of the EQS area.

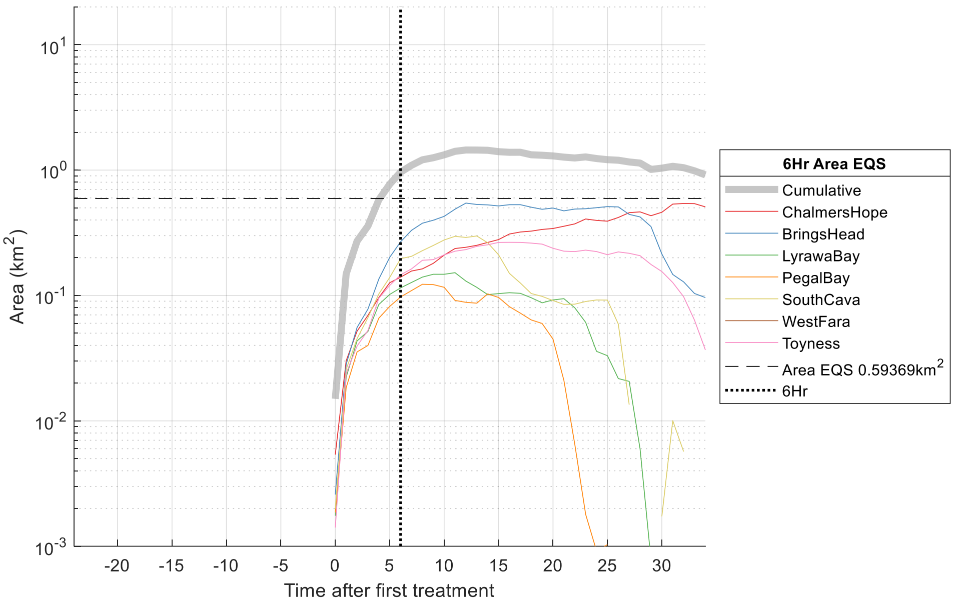


Figure 27. Deltamethrin neap tide area exceeding 6hr EQS value (6 ng/l) for all sites.

The spatial distribution of Deltamethrin 6 hours after the simultaneous release of bath treatments from all sites during a neap tide is shown in figure 28. This indicates the area extent using red contour lines where concentrations exceed time dependent thresholds. The 6hr EQS area identifies small chemical plumes around all sites with licenced chemical usage. At Chalmer Hope the plume is dispersed in the NW direction.

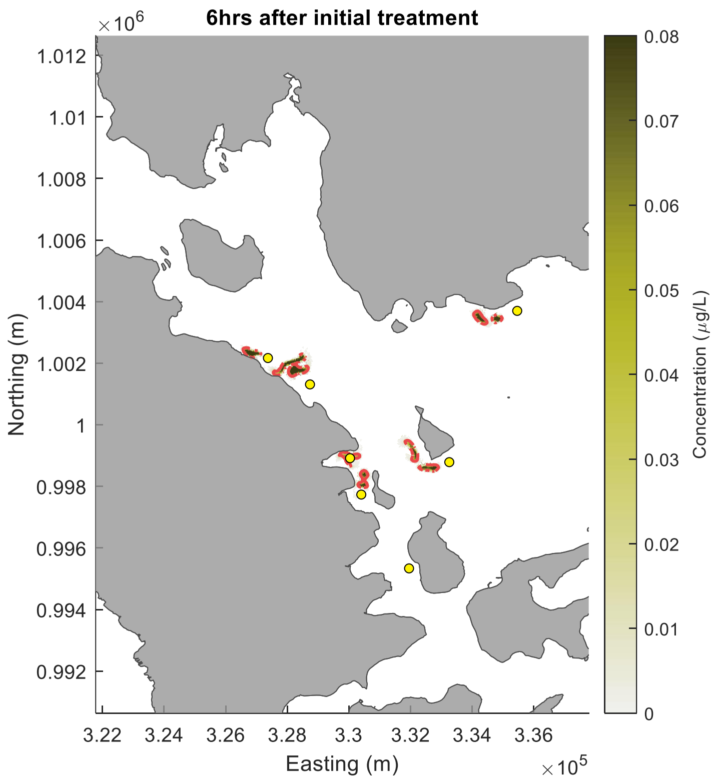


Figure 28. Spatial Deltamethrin distribution for neap tides 6hr after the last treatment event. Areas above EQS values are indicated within the gold contour and site locations are identified using a pink marker.

4.3.3.2 Spring tides

The dispersal of Deltamethrin is calculated for a spring tidal phase. The particle tracking model is started on the 02/03/2018 09:50:00 and finishes on 04/03/2018 19:50:00. The last treatment is administered for all sites on the 03/03/2018 09:50:00. This corresponds to the largest high-water event within the spring/neap cycle.

The MAC for the spring tidal cycle is plotted in figure 29. Chalmers Hope shows peak concentrations in a similar order of magnitude to the surrounding sites. After the final treatment, all plumes are rapidly dispersed, and concentrations are reduced.

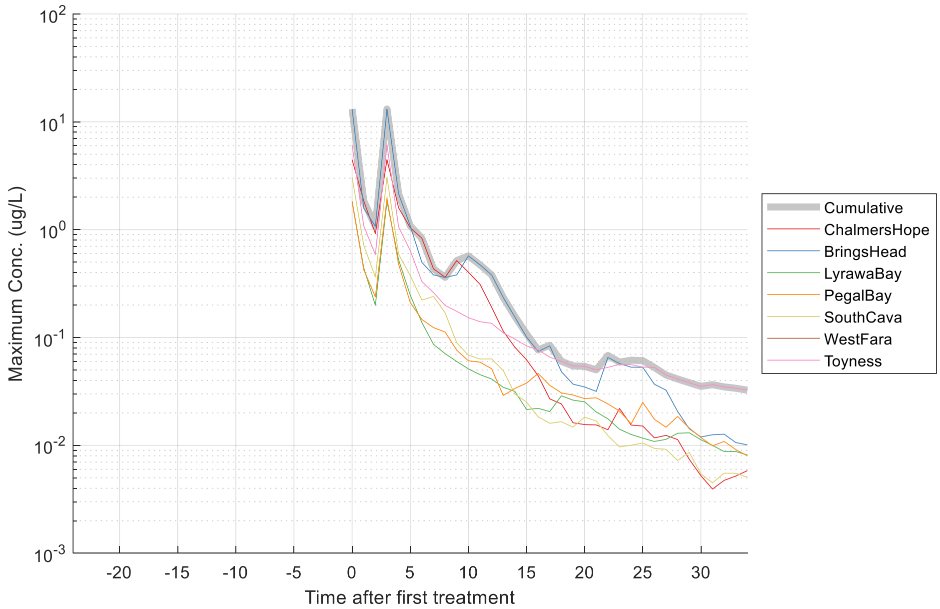


Figure 29. Maximum concentration of Deltamethrin during spring tide release. Cumulative MAC is indicated by grey solid line.

The area exceeding the 6hr EQS value is plotted for the spring tide, this is shown in figure 30. After the first treatment, plume area increases, however all sites show EQS area remains below 0.59km^2. Chalmers Hope shows rapid reduction 16hrs after the first treatment and no values exceeding 6ng/l after 19hrs.

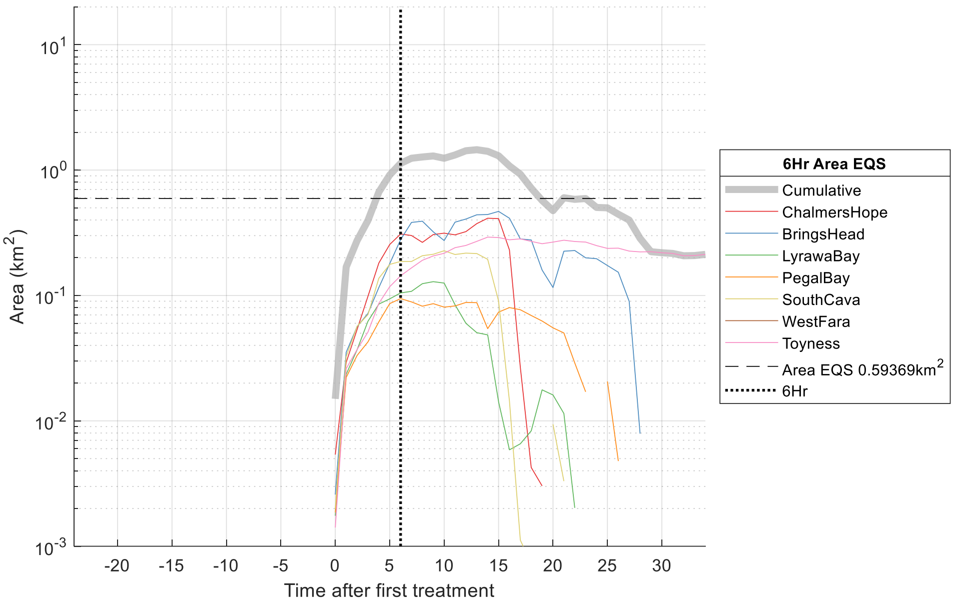


Figure 30. Deltamethrin spring tide area exceeding 6hr EQS value (6 ng/l) for all sites.

The spatial distribution of Deltamethrin after simultaneous release of bath treatments from all sites during a spring tide is shown in figure 31. This indicates the area extent using red contour lines where concentrations exceed time dependent thresholds. The 6hr EQS area identifies smaller chemical plumes located near sites. Compared to the neap tide, the increased advections associated with the spring tides shows plumes from Chalmers Hope and Bring Deeps merging.

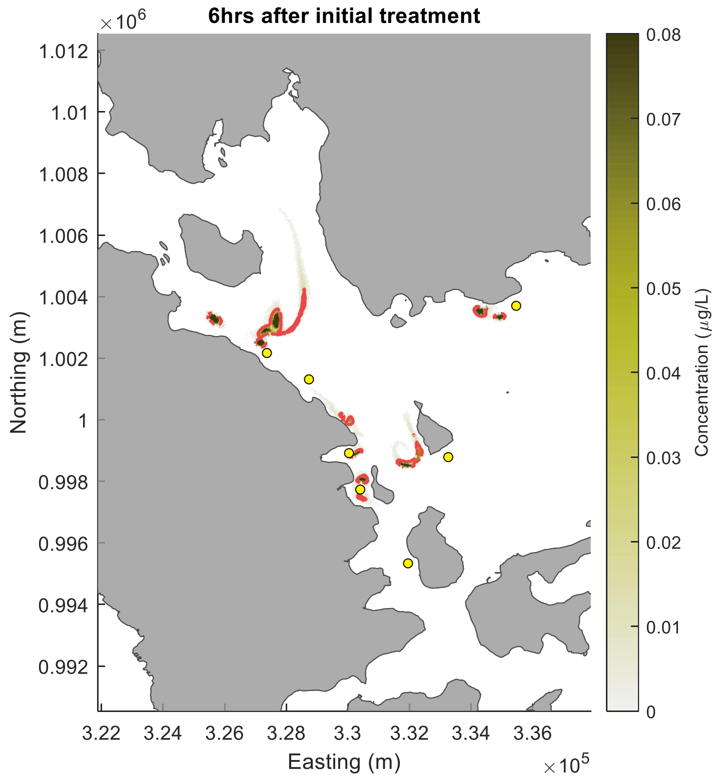


Figure 31. Spatial Deltamethrin distribution for spring tides 6hr after the last treatment event. Areas above EQS values are indicated within the gold contour and site locations are identified using a pink marker.

4.3.3.3 Cumulative assessment

To determine the contribution of the proposed site on the presented cumulative impact, the existing site and a zero-baseline were simulated and compared. The results quantify the area impact at the EQS times, indicating any change relative to the existing and zero-baseline area. The results are shown in table 18. As no Deltamethrin chemical consent was issued for the existing site, the zero-baseline and the existing model outputs are identical. The addition of the proposed treatment plan shows an increase in cumulative impact area of 0.14 and 0.32 km^2, for the respective neap and spring tides. This equates to a percentage area increase of 14.5% and 28.5% for the neap and spring tide.

Table 18. Proposed site influence on cumulative impact.

	6hr EQS	
	Neap	Spring
	All Sites - Area exceeding EQS threshold (km^2)	
All sites (Proposed) (km^2)	0.96	1.13
All sites (Existing) - (km^2)	0.82	0.81
Chalmers Hope site removed (km^2)	0.82	0.81
	Area difference (km^2)	
Proposed vs. Existing	0.14	0.32
Proposed vs. Removed	0.14	0.32
	Percentage difference (%)	
Proposed vs. Existing	14.5	28.5
Proposed vs. Removed	14.5	28.5

The application of 40g of Deltamethrin per pen with a 3hr treatment interval is shown to be compliant with the EQS area criteria. Cumulative modelling of all treatments within the area shows large chemical distributions, where the proposed chemical treatment is shown to have a small contribution to the wider cumulative area coverage.

The simulated treatment quantity provides a recommended consent mass of 40g per 3 hours. This provides a treatable volume of 20,000 m^3 with a concentration of 2000 ng/l. This volume is sufficient to treat 5.9 cone-shaped pens per 3 hours or 13.3 wellboat treatments (1,500m^3 capacity). The depth of the cone-shaped pen is calculated by applying a 25^{o} net angle from the circumference of the pen.

4.3.4 Discussion

The results of the bath treatment simulation provide maximum chemical quantities suitable for maintaining environmental compliance for effective sea lice treatments. This study assumes treatments were administered using either the reduced net depth tarpaulin method or wellboat treatments. Spring and neap tides are simulated to assess dispersion in a range of conditions. The scenarios presented above are purposefully designed to replicate a worst-case chain of events, which lead to larger, more concentrated chemical plumes than normally plausible. The remainder of the discussion identifies these assumptions to discuss the background and validity.

The method of creating a synchronised treatment plan was designed to ensure all farms finished their treatment schedules at the same time. This would allow the accumulation of chemical plumes from all previous treatments to mix, resulting in a large high concentration area coverage. This scenario is highly improbable as it is unlikely all farms will conduct treatments exactly at the same time. In addition, the simultaneous treatment of all sites would require large resources in terms of staff, tarpaulins and wellboats etc. It is unlikely that two operators would have enough infrastructure in place to treat 7 sites at the same time.

Further caution was applied where the horizontal dispersion coefficient was set to the default value of 0.1 m^2/s. This maintains a more cohesive chemical plume, where additional environmental variation from winds and other forcings were removed. It was observed during the dye and drogue study that wind forcing may act as the dominant driver for surface currents and particle dispersal. Under these conditions chemical plumes have a much greater rate of dilution, posing a reduced environmental risk. As sea lice treatments are not limited to calm weather, it is likely that there will be some additional dispersive forces that will act on the chemical plumes resulting faster dilution of treatments.

The proposed model provides a good estimation of the depth averaged flows around the simulated site. However, chemical solutions are presumed to remain within the upper layer of the water column. Due to the intense tidal conditions and complex coastline within Scapa Flow, it is presumed that there will be 3D flow fields with large vertical eddies. While the model does account for minor vertical mixing with a vertical dispersion coefficient of 0.001 m^2/s, the larger more energetic turbulent features are not resolved. To account for these features, a 3D hydrodynamic model would need to be applied. This would also help in accounting for surface wind currents, allowing for a more accurate calibration of particle advection from dye and drogue studies. However, this would incur a substantial increase in the computational resource required.

Currently no chemical half-life is specified for Cypermethrin or Deltamethrin. This does not permit the decay of the chemical in time. While the EQS duration is only 6 hrs after the final treatment, the initial treatments administered may be several days old by the EQS time. This may provide an over estimation in the cumulative impact, where both area and concentrations values maybe elevated. The specification of chemical decay is vital to accurately model the environmental impact and to provide viable alternative treatment options.

5. Conclusions

This report outlines the methodology and results for the simulation of particulate organic waste and bath treatment chemicals at the proposed Chalmers Hope site. The work presented in this report addresses the concerns regarding Priority Marine Features and cumulative farm effects highlighted in the Chalmers Hope screening modelling and risk identification report by SEPA (2020), as well as deriving appropriate bath chemical quantities that are compliant with EQS standards.

A validated hydrodynamic model was applied to simulate far field deposition and bath treatments for the proposed Chalmers Hope site. The flow model validation showed excellent agreement with multiple datasets for water level and east and north velocity components. Wind forcings were removed to exclude potential storm conditions that would result in irregular particle advection.

A dye and drogue release study were commissioned to determine the horizontal dispersion at the Chalmers Hope site. A mean horizontal dispersion coefficient of 0.207 m^2/s was calculated directly from the dye release data. A particle tracking model was used to replicate dye and drogue releases. This provided an optimal horizontal dispersion coefficient of 0.3 m^2/s. Increased wind speeds during the release window caused dominant surface flows, driving dye and drogue dispersion. While these conditions are within the normal operational weather conditions, a lower dispersion coefficient of 0.1 m^2/s provides a more conservative and potentially representative value in calm meteorological conditions.

To explore the cumulative benthic impacts of particulate organic waste, particles representing waste fish feed and faeces were released in a particle tracking model, driven by the calibrated and validated hydrodynamic model. The results demonstrate the highly dispersive nature of the proposed Chalmers Hope site, with only a small accumulation of sediment (mean concentration <50 g/m^2) within the 100m mixing zone of the site. When considering the release of particulate waste from all sites within the west Scapa flow domain, less than 0.1% of all identified PMFs were impacted. This suggests the cumulative risk to these sensitive regions is exceptionally small. The cumulative benthic impact for all sites within west Scapa Flow provides an area equal to 1.78 km^2, this is proportional to 0.68% of the waterbody area. The expansion and repositioning of the Chalmers Hope sites results in a 0.29km^2 increase in the cumulative impacted area (equivalent to 0.11% of the waterbody area) , when comparing the depositional footprint of the existing and proposed Chalmers Hope sites. The difference in the impacted area between including the proposed site and omitting the proposed site indicates that the new Chalmers Hope site contributes 0.42km^2 (23.1%) to the wider impacted area. The extent of this area is considered to be an overestimation as particle parameters were assigned using conservative estimates and sites are stocked using a maintained maximum biomass.

A second particle tracking model was used to determine environmental compliance when using a range of bath treatments. Particle releases were designed to replicate realistic treatment regimes, this used 3 treatments per day with a 3 hourly interval. For Azamethiphos, a recommended consent mass of 785g per 24 hr period and 466.67g per 3 hr window was shown to be compliant with EQS. This equates to a treatment volume of 1.7 wellboat treatments (1,500m^3 capacity). Cypermethrin achieved a recommended consent mass of 0.059925g per 3 hour period. This chemical quantity is not viable for the effective treatment of sea lice. Deltamethrin provided a recommended consent mass of 40g per 3 hours, while maintaining EQS compliance. This provides a treatable volume equal to 13.3 wellboat treatments (1,500m^3 capacity). The isolated impacts associated with Chalmers Hope shows small impact areas that remain below the calculated mixing areas for the relevant EQS times and concentrations. When cumulative impacts are assessed, Chalmers Hope is shown to have a minor contribution to the wider impact area.

The numerical simulation of bath treatments has shown successful treatment options using Azamethiphos and Deltamethrin. The application of these treatments is shown to be compliant with EQS. The treatment of sea lice is not restricted to medicinal approaches, in some cases thermal or mechanical treatment options can be used. This provides a diverse range of sea lice treatment options that can be called upon if required. This allows specific treatment plans to be chosen that are best suited for the welfare of the farmed fish, wild fish and the wider environment.

6 References

Anderson Marine Surveys (2021) "Cooke Aquaculture Chalmers Hope dye dispersion study".

Greenwood (2019) "Chalmers Hope Modelling Data Collection Report".

Greenwood (2021) "Chalmers Hope Marine Modelling Methods Statement".

SEPA (2007) Water Framework Directive (WFD) Waterbody Classification 2007-2017 (Accessed 12/2021) Available at: http://marine.gov.scot/maps/1110

SEPA (2020) AQUACULTURE MODELLING SCREENING & RISK IDENTIFICATION REPORT: Chalmers Hope (CHA1). (Accessed October 2021). https://www.sepa.org.uk/media/524919/cha1_screenmodriskid.pdf

SEPA (2018) Supporting Guidance (WAT-SG-53): Environmental quality standards and standards for discharges to surface waters. Available at https://marine.gov.scot/sma/content/supporting-guidance-wat-sg-53-environmental-quality-standards-and-standards-discharges (accessed October 2021)

UK Hydrographic Office (2021) Marine Data Portal (Accessed 05/2021) Available at: https://datahub.admiralty.co.uk/portal/apps/sites/#/marine-data-portal

Weather Underground (2021) "Kirkwall Airport Station Weather History for 12/06/2021". Available at https://www.wunderground.com/history/daily/gb/kirkwall/EGPA/date/2021-6-12 (Accessed on 04/10/2021).

7 Appendix 1

7.1 Proposed biomass increase at Brings Head and Toyness

To anticipate future changes to the cumulative benthic impact in the west Scapa Flow region, an additional model was ran simulating the expansion of the Scottish Sea Farm sites, Brings Head and Toyness. This proposes an increased maximum biomass from the respective existing values of 968t and 1343t to a proposed biomass of 2500t. The resultant quantities of waste and excreted solids from these proposed sites are given in table A1.

Table A1. Particle mass per model timestep.

Site	Biomass (t)	Waste feed (kg)	Excreted Solids (kg)
Proposed Brings Head	2500	19.90625	96.54531
Proposed Toyness	2500	19.90625	96.54531

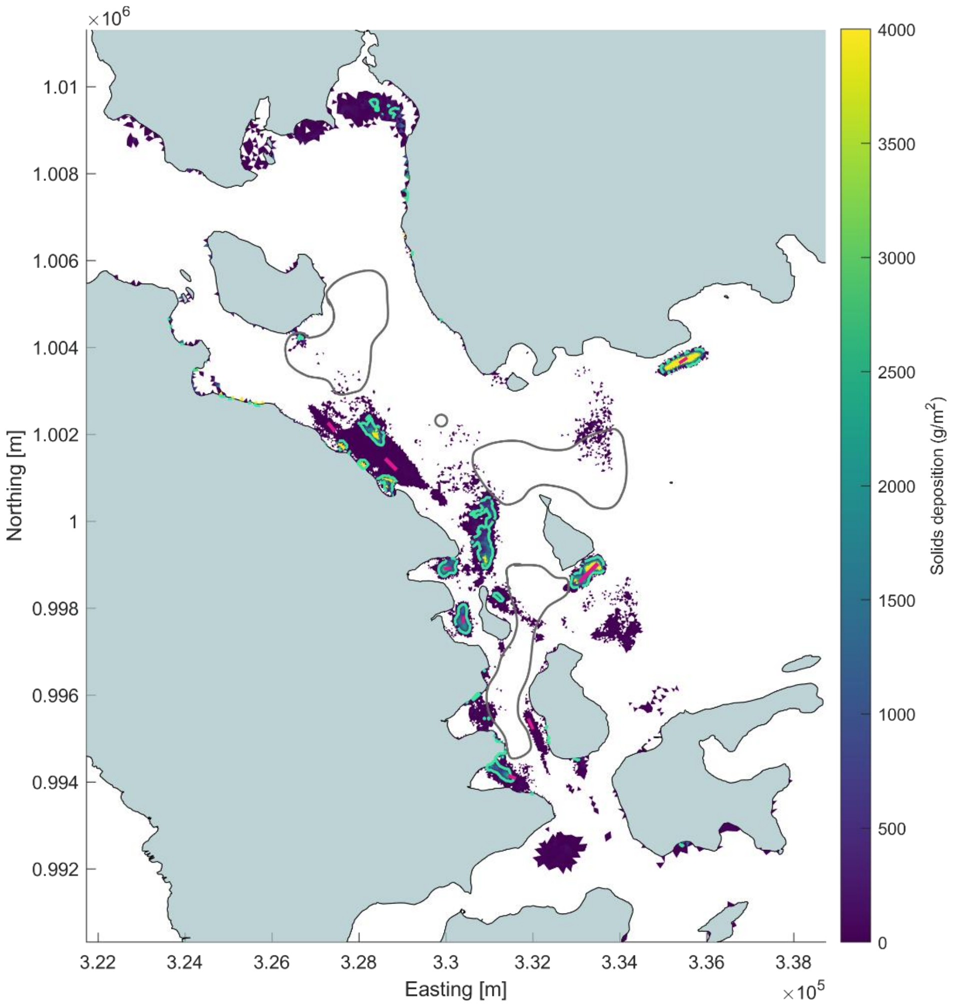


Figure A1 – Mean deposited solids concentration from proposed Chalmers Hope, Toyness and Brings Head and neighbouring licensed sites over the final 90 days of the model run period. The location of licensed farms (pink rectangles) and sensitive marine features (grey outline) in the region are also shown. Impacted seabed (>250g/m^2) is highlighted by the light blue contours.

The spatial coverage of depositional solids released from the proposed Chalmers Hope, proposed Brings Head, proposed Toyness, existing Lyrawa Bay, Pegal Bay, South Cava, West Fara and Ore Bay sites is shown in figure A1. The concentrations displayed represent the mean of the final 90 days of the particle tracking model run. Concentration values of less than 1g/m^2 have been excluded from the map and all subsequent figures. Such low concentrations are not considered to be representative of the main influence of a discharge (SEPA, 2020). Predicted impact areas are defined as those with deposited concentrations of 250g/m^2 or higher.

The increased waste released from the larger proposed Brings Head and Chalmers Hope sites combines to produce a small increase in concentrations of deposited solids immediately surrounding the two sites and within Clestrian Sound. However, this increase is not substantial enough to significantly increase the spatial extent of impacted seabed (>250g/m^2). The increase in waste released from the proposed Toyness site is predominantly deposited in close proximity to the farm, resulting in increased concentrations immediately surrounding Toyness.

Timeseries of the percentage area within each sensitive marine feature that exceeds the EQS intensity threshold of 250g/m^2 are shown in figure A2. Approximately 0.13% of all PMFs, identified in the Chalmers Hope Screening modelling and risk identification report by SEPA (2020), were impacted.

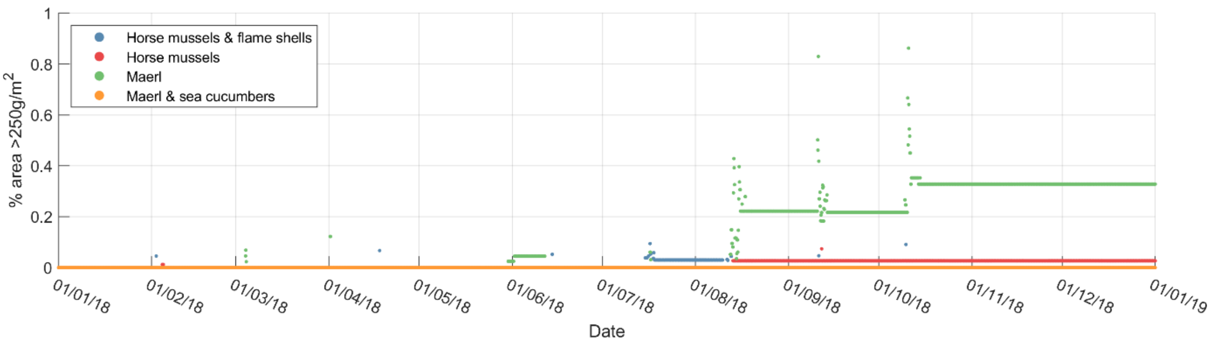


Figure A2 – Model run timeseries of the percentage area of the sensitive marine features that exceeds the EQS threshold.

The predicted impact area of deposition from all sites, defined as regions enclosed by the 250g/m^2 contour corresponding to an equivalent IQI of 0.64, is 1.97 km^2 (figure A3). This is equivalent to 180.1% of the combined 100m mixing area, if the cage circumference and grid spacing of Brings Head and Toyness are assumed to increase to 120m and 70m, respectively, to accommodate the increased biomass. A predicted mean deposition of 1988.6 g/m^2 occurs across the predicted impact areas.

The intensity of the predicted cumulative benthic deposition for the proposed Chalmers Hope, Toyness and Brings Head sites plus 5 surrounding sites is below the EQS level of 2000g/m^2. However, the spatial extent of the predicted impact is above the threshold EQS parameter of 100% of the 100m mixing zone area.

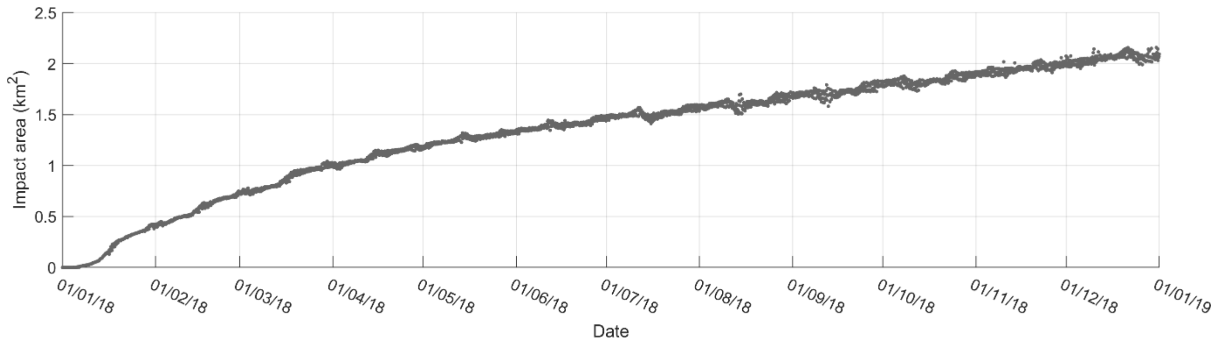


Figure A3 – Model run timeseries of impact area (>250g/m^2) spatial extent from the proposed Chalmers Hope, Brings Head and Toyness sites plus surrounding sites.