CLAWS – Chemicals Lice and Waste from Salmon Farms

2. Bath Treatments

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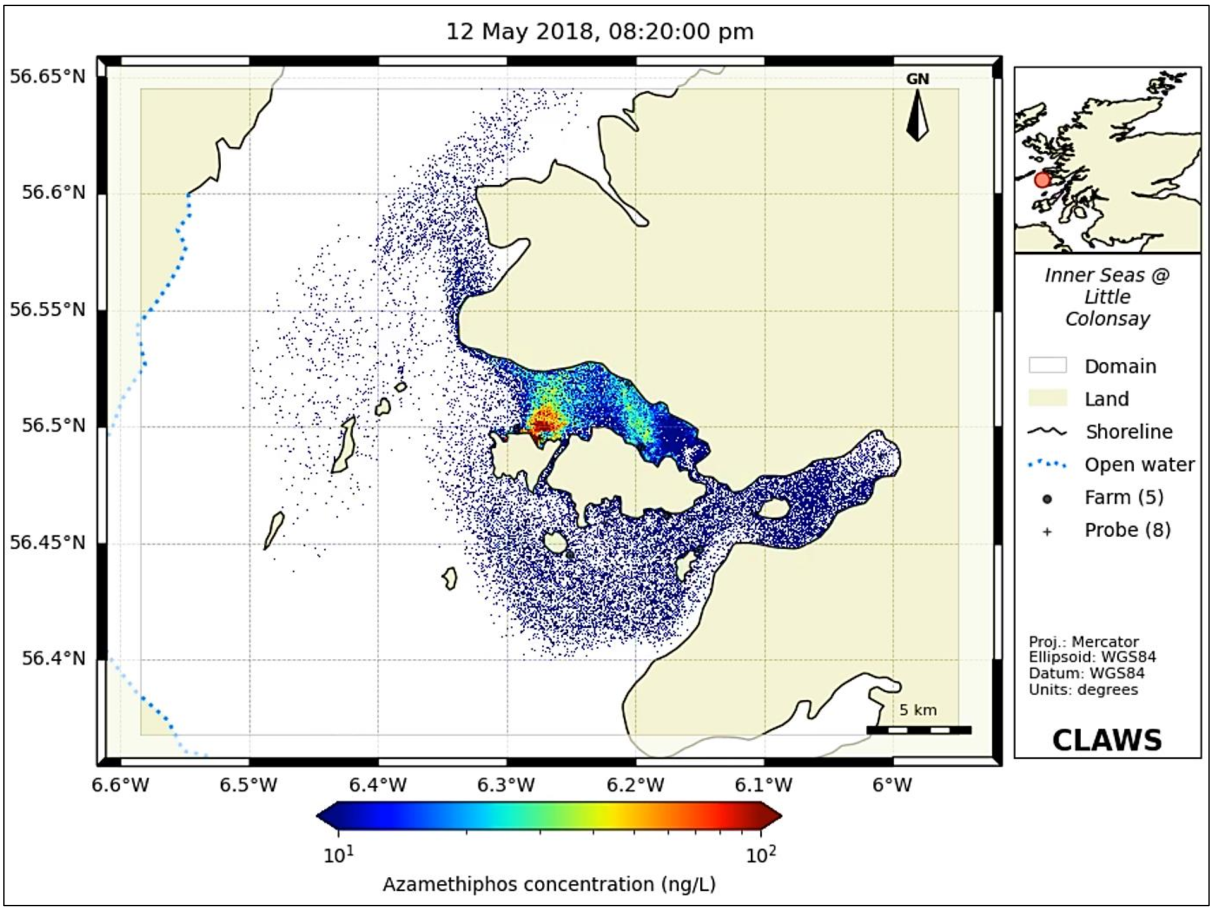


Executive Summary

A particle-based bath treatment model has been developed for application in salmon farms in semi-enclosed sea lochs and open sea areas. The bath treatment model is part of a suite of particle-based, open-source modules known as CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS, 2023]. Other particle modules in the CLAWS repository include those to describe hydrodynamics, nutrients and particulate waste deposition from finfish farms. The bath treatment model calculates the pesticide concentration in the marine environment and comparison is made against the statutory SEPA standards for Maximum Allowable Concentration (MAC) and Environmental Quality Standard (EQS). A 3D hydrodynamics model based on the Telemac code is used to drive the particle-based bath treatment calculation. The hydrodynamics model contains the influence meteorological forcing and stratification brought about by freshwater inflows and air-water heat exchange. For the Lagrangian particle-tracking, the open-source code OpenDrift [OpenDrift, 2023] has been used. Results show that the bath treatment code can successfully predict pesticide distributions and present the concentrations in a format suitable for scientific reporting. Pesticide dispersion patterns show localised concentrations in excess of the MAC value of 100 ng/L in the inner seas north of Ulva and Gometra. Analysis of the results shows that the 3-hour EQS (250 ng/L) is likely to be breached across the entire 11-day period of the dispersion. 3 days following the final bath treatment, both the 72-hour EQS (40 ng/L) and MAC (100 ng/L) are shown likely to be breached. Throughout the entire 11-day dispersion simulation the area over the EQS (0.5 km^2) is likely to be exceeded. The area over the MAC (0.5 km^2) is exceeded sporadically but falls below the SEPA threshold level 3-days following the last bath treatment. Azamethiphos concentrations at specific locations around the inner seas at Little Colonsay show that peak concentrations in excess of the EQS and MAC values are likely to occur.

About the Report Authors

Dr Tom Scanlon *BEng PhD CEng MIMechE, Engineering Consultant, MTS-CFD.com*

Tom is a chartered professional engineer with over 25 years' experience in applied computational mechanics. After a first degree in Environmental Engineering at the University of Strathclyde, Tom undertook a Ph.D in Vortex Shedding Flowmeter Pulsating Flow Computational Fluid Dynamics (CFD) Studies at the same university. Subsequently, he was awarded a JM Lessels scholarship from the Royal Society of Edinburgh for a one-year post-doctoral position at the Institute de Mécanique des Fluides de Toulouse, France in the field of numerical oceanography. The IMechE presented Tom with the Alfred Rosling Bennett Premium and Charles S Lake Award in 2003 for CFD in applied aerodynamics. In 2013 Tom returned from an EPSRC-funded sabbatical in the USA, where he carried out fundamental research in rarefied gas dynamics at the University of Michigan and the Lawrence Berkeley Laboratory in California. From 1994-2017 he was a Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the University of Strathclyde specialising in heat transfer, fluid mechanics and applied CFD. His work is reported in over 50 refereed journal and conference publications. He is currently a director at the engineering consultancy firm MTS-CFD.

***Dr Vincent Casseau** MSc PhD, Engineering Consultant*

Vincent is an engineering consultant with background experience in fluid dynamics and computer science. He obtained his Masters engineering degree in Aeronautics and Aerospace at ISAE-ENSMA, Poitiers, France. Following an internship at the European Space Agency, Vincent undertook a Ph.D in high-speed re-entry physics at the University of Strathclyde under the supervision of Dr Tom Scanlon, where he developed an open-source platform to solve hypersonic continuum and rarefied flows that has since been used in 15+ countries. Vincent was a Postdoctoral Fellow at McGill University in Montreal, Canada from 2019-2021, where he co-led the development of a monolithic software system to simulate hypervelocity civilian craft, partnering with Ansys and Lockheed Martin.

***Dr Matt Stickland** BSc PhD CEng FIMechE, Engineering Consultant, MTS-CFD.com*

After a first degree in Aeronautical Engineering at the University of Manchester, Matt worked for BAE Systems (Military Aircraft) at Warton in Lancashire in the Wind Tunnel Department working on projects which included EAP, EFA (Typhoon), Tornado and HOTOL. After leaving BAE in 1990 Matt worked for YARD Consulting Engineers in Glasgow modelling the heat and fluid flows in Advanced Gas Cooled reactors during on-load refuelling. In 1991 Matt accepted a senior lectureship in the Department of Mechanical Engineering at the University of Strathclyde where his research interest covered both experimental and computational heat transfer and fluid dynamics. He was awarded a PhD for his research into 3D imaging and its application to fluid flow visualisation. For his research in the field of experimental and computational fluid dynamics he was awarded the 2003 AR Bennett Premium/CS Lake Award and the 2004 T A Stewart-Dyer Prize/Frederick Harvey Trevithick Prize from the Institute of Mechanical Engineers. In 2022 Matt left the University of Strathclyde to take a directorship with the Engineering consultancy firm MTS-CFD. Matt is a Chartered Engineer and a Fellow of the Institute of Mechanical Engineers. He has published his research in over 100 papers in refereed journal and conference proceedings.

1 Introduction and motivation

This report has been prepared by engineering consultants MTS-CFD, as part of hydrodynamic modelling services to consider the impact of pesticides emanating from existing and proposed fish farms on the West Coast of Scotland.

Operational fish farms have the potential to affect the marine environment in several ways, via the release of waste in the form of dissolved nutrients, particulate organic matter, pesticides and live parasitic salmon lice.

Bath treatments are chemical treatments used in marine cage fish farms to treat infestations of parasitic sea lice. The process involves reducing the cage volume by raising the net to a specified treatment depth. The cage is surrounded by a tarpaulin and a predetermined amount of pesticide is added. A treatment period typically lasts up to one hour after which the tarpaulin is removed and the cage net lowered allowing water to flow through and disperse the chemical. The purpose of the modelling is to determine the post-treatment concentration levels in the marine environment and compare these to SEPA statutory Environmental Quality Standards (EQS) and Maximum Allowable Concentration (MAC).

The report describes the application of a particle-based bath treatment model to determine pesticide concentrations in the marine environment when released from salmon farms. The bath treatment model is part of a suite of particle-based, open-source modules known as CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS, 2023]. Other particle modules in the CLAWS repository include those to dissolved nutrients and particulate waste deposition from finfish farms.

A 3D hydrodynamics model based on the TELEMAC code [Scanlon_A, 2023], [Scanlon_B, 2023] is used to drive the particle-based pesticide dispersion calculation. The hydrodynamics model contains the influence of weather forcing and stratification through the salinity and temperature fields.

2 Background data

2.1 *Site location*

The proposed site location of the Bakkafrost salmon farm is off of the West coast of Mull, adjacent to the island of Little Colonsay as shown in Figure 1.

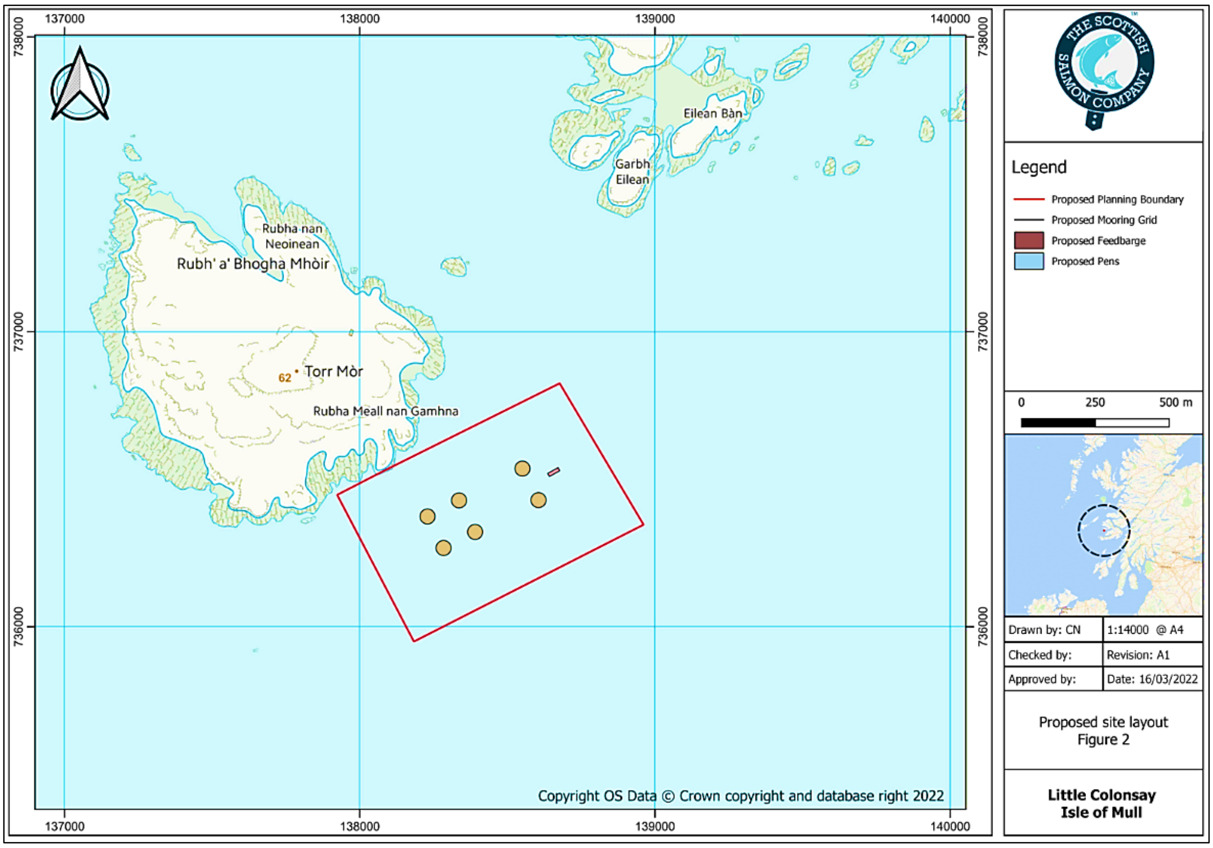


Figure 1 *Geographic location of the proposed Bakkafrost salmon farm at Little Colonsay (inset on lower right shows the general location).*

2.2 *Hydrodynamic model*

The hydrodynamic data used to determine the flushing times is based on a 3D, non-hydrostatic Telemac model of the West Coast of Scotland, the extent of which is shown in Figure 2. 10 terrain-following vertical sigma layers are applied in the model and it also includes meteorological forcing and stratification due to freshwater inflows and atmosphere-water heat exchange. Extensive validation and verification tests have been undertaken against physical data and inter-model comparisons with the Scottish Shelf Model (SSM) results [Scanlon_A, 2023], [Scanlon_B, 2023] and at Little Colonsay itself [MTS_CFD_hydro_LC, 2023].

2.3 *Bathymetry data*

The bathymetry data for the present study have been collected from a range of different sources including publicly available data sets provided by Marine Scotland for the Scottish Shelf Model [SSM, 2023], digitised Admiralty charts and bathymetry information from the UK's Digimap Ordnance Survey Collection [DOSC, 2023]. The bathymetry used in the model is shown in Figure 3.

2.4 *Particle-tracking*

For the Lagrangian particle-tracking the open-source software OpenDrift has been used [OpenDrift, 2023].

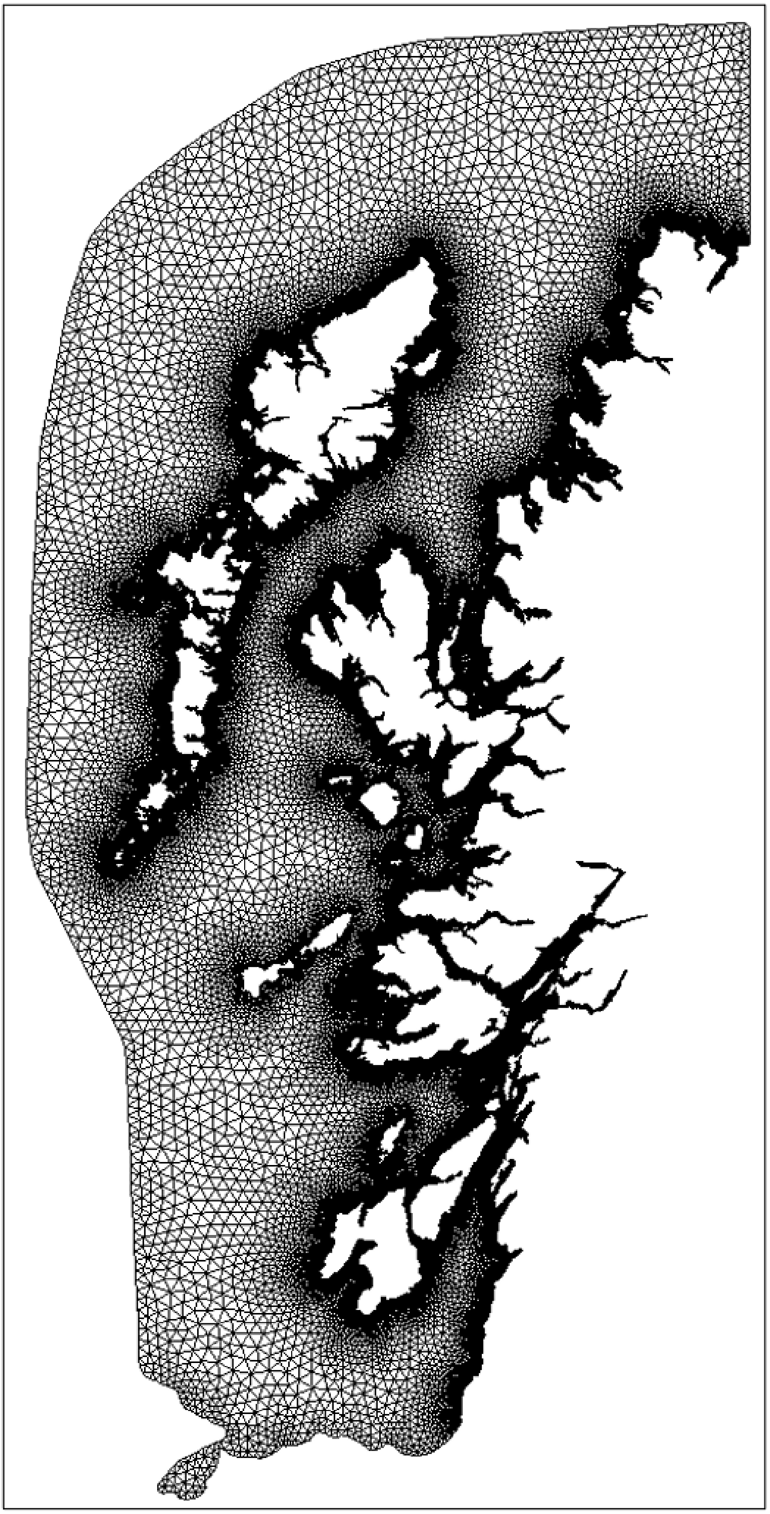


Figure 2 *Telemac 3D hydrodynamic mesh and model extent.*

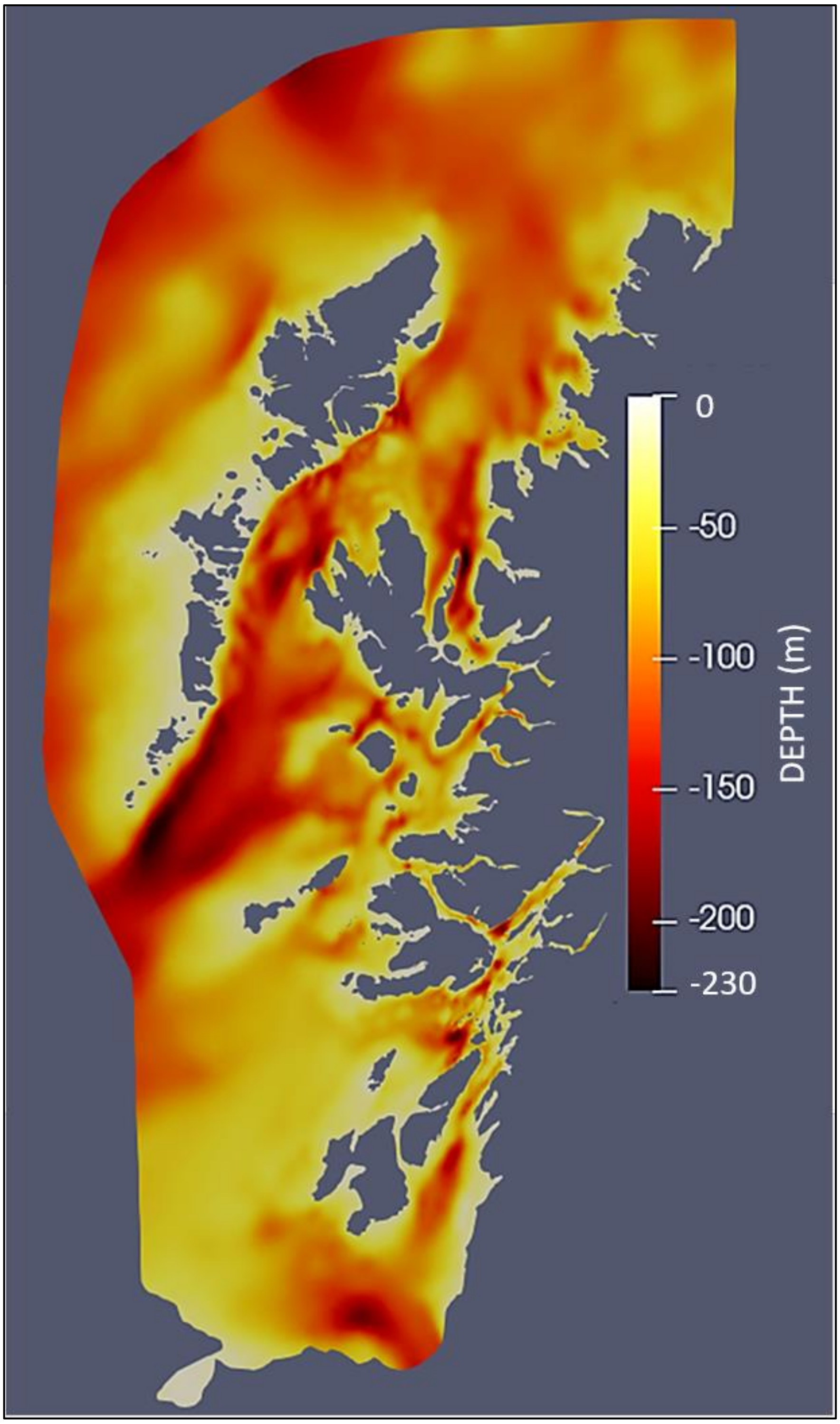


Figure 3 *West Coast model bathymetry (m).*

3 Methodology

3.1 *Shoreline database*

The shorelines delineating land and water areas are obtained from the GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography) database [WESSEL, 1996]

[DAGESTAD, 2018] and the highest possible resolution is applied. This allowed the shorelines and computational mesh to be constructed using the freely-available BlueKenue software [BLUEKENUE, 2011]

2.4 *Particle-tracking of pesticides*

For the Lagrangian particle-tracking the open-source software OpenDrift has been used [OpenDrift, 2023]. The approach for bath treatments is the same as for living organisms such as sea-lice, except that pesticide has no biological behaviour but instead undergoes chemical decay: the numerical particles in the model represent “parcels” of pesticide of known mass, which reduces over time at a rate determined by a specified half-life. Particles are released at pen locations at specified times, according to a treatment schedule. The number of particles combined with their initial mass represents the mass of pesticide required to treat a pen. The particles are then subject to advection, from the modelled flow fields, horizontal and vertical diffusion, and chemical decay. Concentrations of pesticide can be calculated throughout the simulation (e.g., 72 hours after the final treatment) and compared with relevant statutory standards. Here, we have modelled the dispersion of Azamethiphos following treatment scenarios at Little Colonsay to illustrate the quantities of pesticide that disperse into the marine environment.

2.5 *Bath treatment schedule*

Including the proposed salmon farm, there are a total of 5 sites in the Little colonsay system. The farm locations are shown in Figure 4 and the biomasses, taken from the SEPA screening document [SEPA_SCRN, 2023], are shown in Table 1.

The treatment schedule and dosage levels of Azamethiphos for each farm is shown in Table 2 [AQUA_SCOT, 2023]. Note that the Azamethiphos dosage level for the Little Colonsay farm was set as 407 g based on the size of the farm, scaled against other farms in the area.

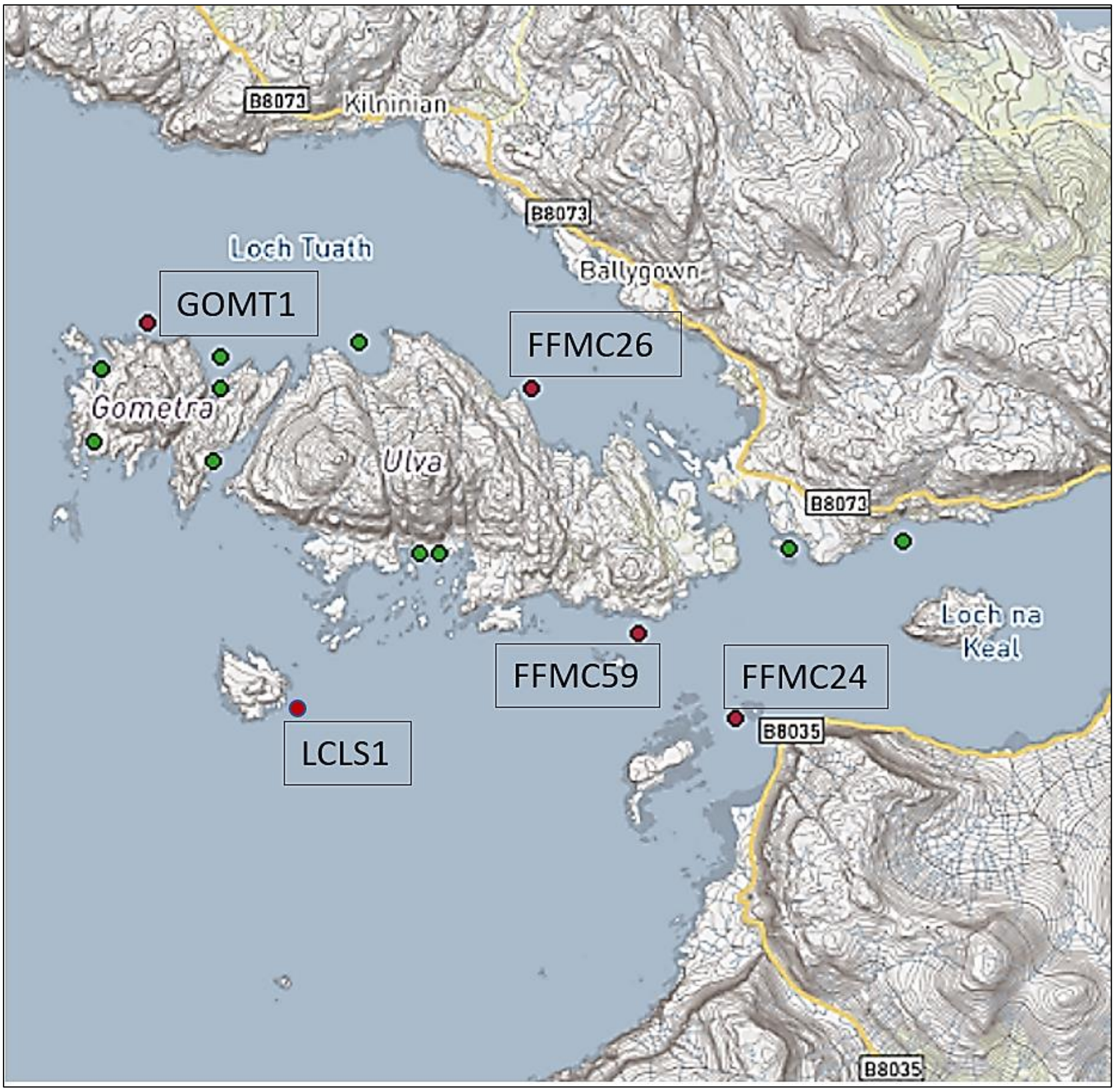


Figure 4 *Location of the 5 salmon farms in the Little Colonsay system highlighted by red dots. Green dots are active shellfish farms. Farm locations taken from [AQUA_SCOT, 2023].*

Table 1 *Salmon farm biomasses in the bath treatment calculation [SEPA_SCRN, 2023].*

Site ID	Name	Biomass (tonnes)
LCLS1	Little Colonsay	2773
GOMT1	Gometra	1944
FFMC26	Tuath	850
FFMC24	Inch Kenneth	270
FFMC59	Geasgill	2500

Table 2 *Treatment schedule and dosage levels of Azamethiphos. Aza data from [AQUA_SCOT, 2023] while Aza data for Little Colonsay has been estimated.*

SITE	Aza 24-h limit (g)	No. of Cages	Treatment Schedule (cages per day)
Little Colonsay	407	6	2
Gometra	636.6	16	2
Tuath	154.2	12	2
Inch Kenneth	158.41	10	2
Geasgill	219.7	12	2

2.6 *Shoreline database*

The shorelines delineating land and water areas are obtained from the GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography) database [WESSEL, 1996] [DAGESTAD, 2018] and the highest possible resolution is applied. The shorelines were then constructed using the freely-available BlueKenue software [BLUEKENUE, 2011].

2.7 *Modelling approach*

The modelling approach employed a coupled hydrodynamic and particle tracking method, whereby water currents in the region, modelled using the 3D hydrodynamic model, advected particles representing the bath treatment pesticide around the model domain. Turbulent eddy diffusion was modelled using a random walk approach with the horizontal and vertical eddy-diffusivities set to 0.1 and 0.001 m^2/s, respectively. Outputs from the modelling were derived to assess the dispersion of the pesticide following treatments against statutory Environmental Quality Standards (EQS) and Maximum Allowable Concentrations (MAC).

3 Pesticide dispersion modelling

3.1 *Reducing the size of the hydrodynamics data set*

The 3D Telemac hydrodynamics model consists of a large data set of flow variables with a file size of 36 Gb. It would be beneficial in terms of disk storage and compute time for the bath treatment model if the hydrodynamic data set could be reduced in size to one focusing on the environment around Little Colonsay. A Python script has been created to achieve this reduction using the format JSON (JavaScript Object Notation) [JSON, 2023]. JSON is used to select the reduced hydrodynamics area for the bath treatment calculation. It is a lightweight file format storing text as a series of keyword – value pairs and its extension GeoJSON conveniently encodes geographic data structures. The website http://geojson.io/ allows the user to draw a polygon around the geographic area of interest. The example of Little Colonsay is shown in Figure 5 and the polygon is saved in GeoJSON format for use in the Python script.

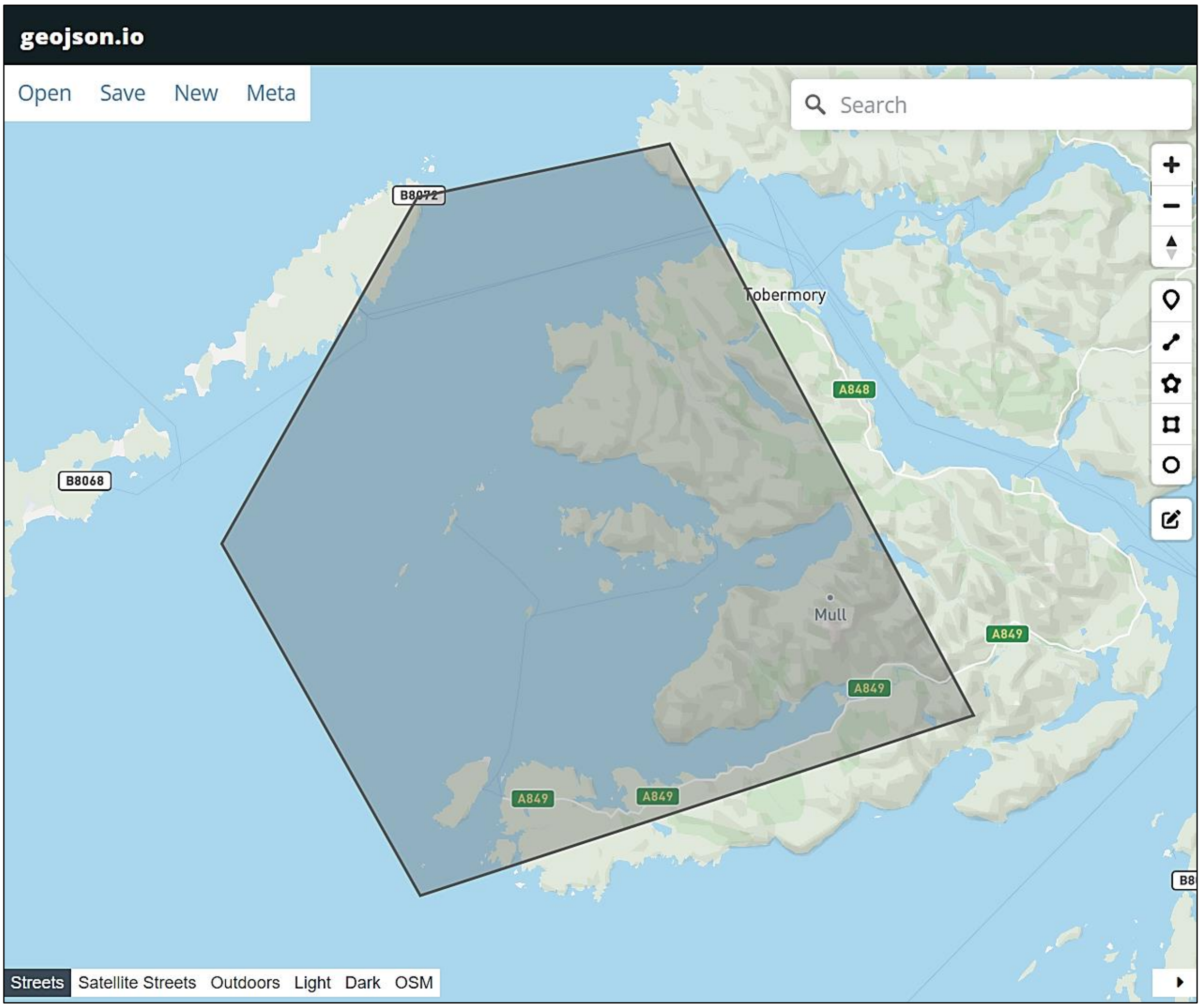


Figure 5 *Polygon selection for setting the reduced hydrodynamics area for the pesticide dispersion calculation at Little Colonsay.*

The file size for the hydrodynamics is reduced substantially from 36 Gb to 0.65 Gb. Figures 6 and 7 show the original model mesh (36 Gb, blue) and the cropped model (0.65 Gb, red) that is used for the pesticide dispersion calculation. Figure 8 shows the final CLAWS reduced mesh following the application of the Python script.

Figure 6 *Original Telemac 3D hydrodynamics mesh (36 Gb, blue) and reduced size model (0.65 Gb, red).*

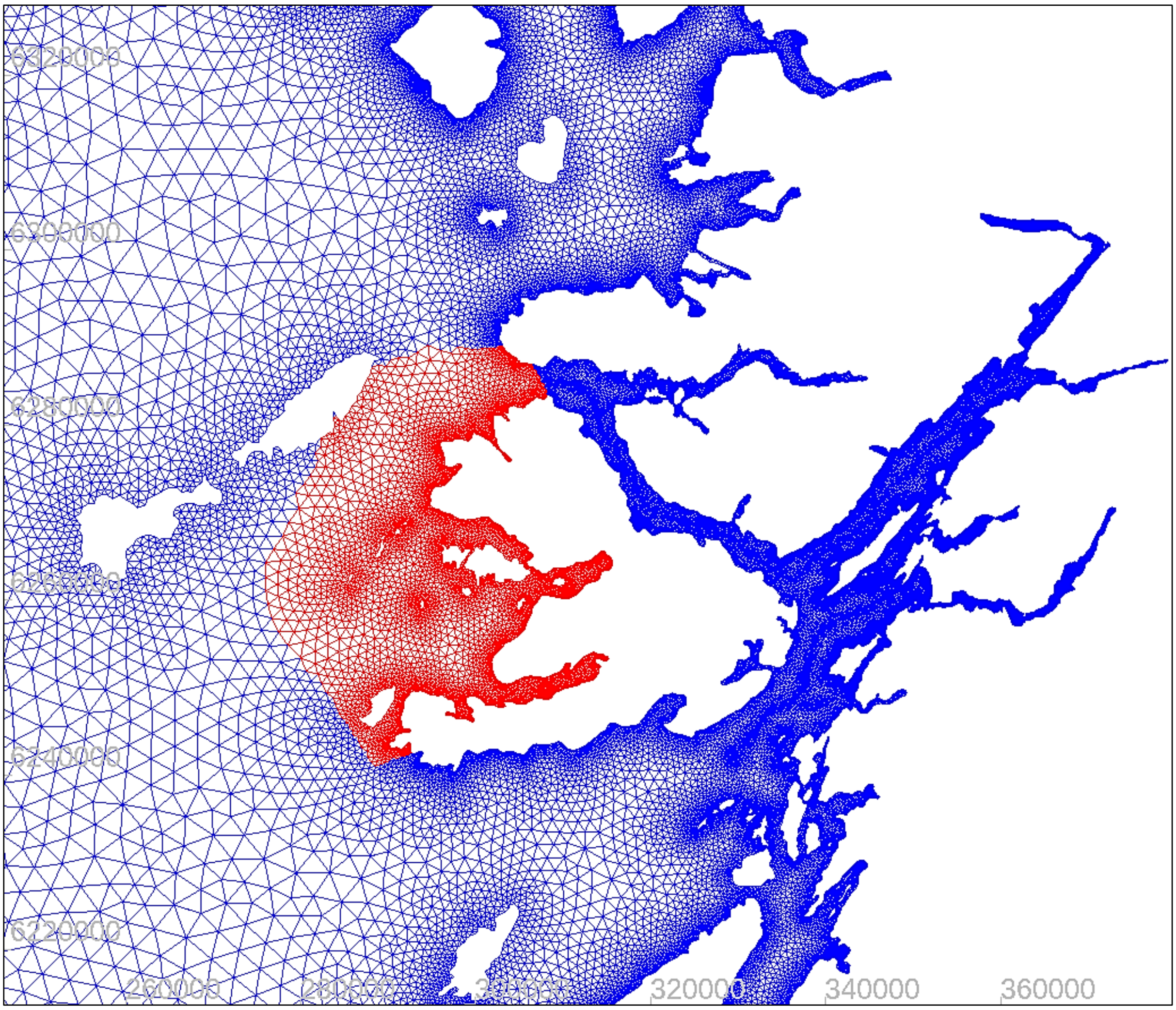


Figure 7 *Zoomed view of original Telemac 3D hydrodynamics mesh (36 Gb, blue) and reduced size model used for the pesticide dispersion (0.65 Gb, red).*

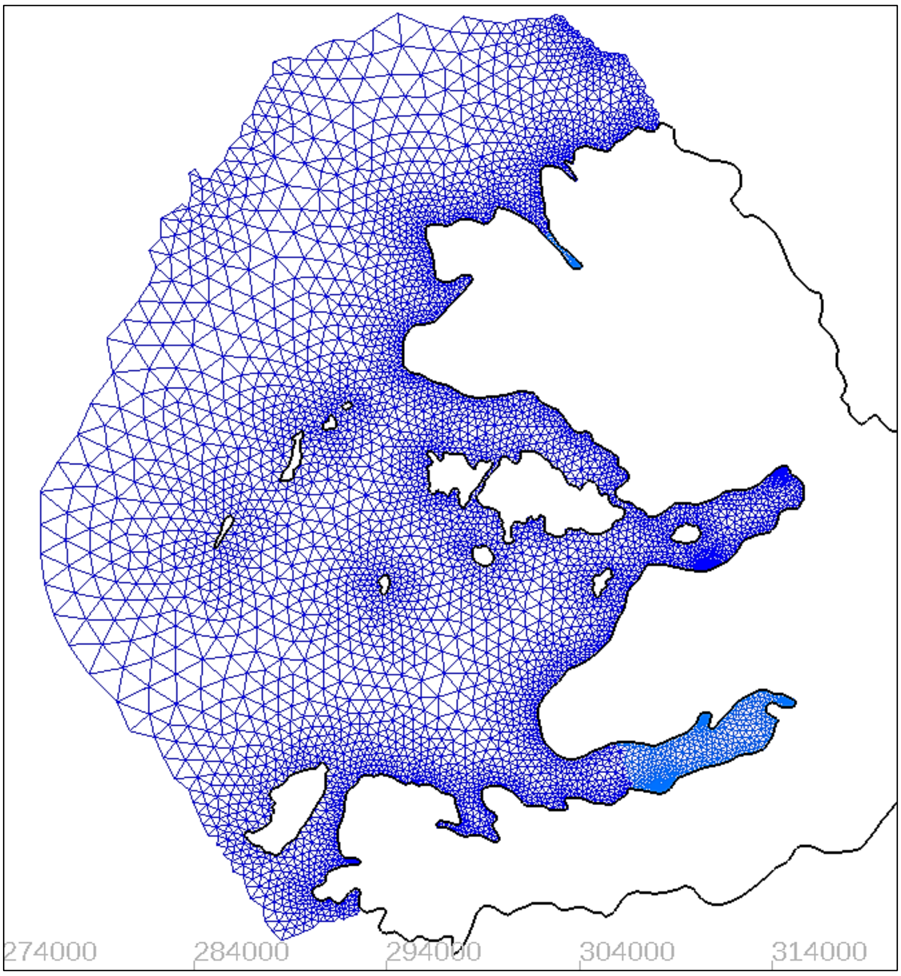


Figure 8 *Final reduced size 3D computational mesh in the Little Colonsay area.*

3.2 *SEPA Environmental Quality Standards (EQS)*

The Environmental Quality Standards (EQS) and Maximum Allowable Concentration (MAC) levels for the bath treatment chemical Azamethiphos used at Loch Hourn is shown in Table 3 [SEPA, 2023].

Table 3 *SEPA EQS and MAC values*

	Timescale	Standard	Type
Azamethiphos	3 hours	250 ng l-1	EQS
	72 hours	40 ng l-1	EQS
	72 hours	100 ng l-1	MAC

Azamethiphos remains in solution for a period of time before it is broken down into non-toxic derivatives. Two standards are applied, one at 3 hours after any discharge and the other 3 days after the final discharge in any treatment period. SEPA applies the 72-hour EQS out with an allowable zone of effect (AZE) which for Azamethiphos is defined as the lower of 0.5 km^2 or 2% of the loch area. The EQS may be exceeded within the AZE, subject to the condition that the peak concentration does not exceed the maximum allowable concentration (MAC). Two sensitivity analyses were conducted by setting the half-life of Azamethiphos to be 5.6 days or 8.9 days.

3.3 *Pesticide dispersion modelling*

The pesticide dispersion modelling, performed using the CLAWS Bath Treatment software [CLAWS, 2023], simulates the dispersion of patches of pesticides discharged from pens following treatment using tarpaulins. The bath treatment model uses the cropped mesh hydrodynamic model (Figure 8), and reads the flow fields directly from the hydrodynamic model output files. The model was run for a period of 11 days from the 4th May 2018 at 7 a.m. which covered the neap tide cycle shown in Figure 9.

This also covered the treatment period (168 hours), a dispersion period to the EQS assessment after 240 hours (72 hours after the final treatment), and an extra 24 hours to check for chance concentration peaks. At every 10 mins of the simulation, particle locations and properties (including the decaying mass) were stored and subsequently concentrations calculated. Concentrations were calculated on a sampling grid of 20 m × 20 m squares using the same depth range as the treatment depth (i.e., 0 – 3 m). From the calculated concentration fields, time series of three metrics were constructed for the whole simulation: (i) The maximum concentration (ng/L) anywhere on the sampling grid; (ii) The area (km^2) where the EQS was exceeded; (iii) The area (km^2) where the MAC was exceeded. These results were used to assess whether the EQS or MAC was breached after the allotted period (72 hours after the final treatment).

Particles were released from random positions within a pen radius of the centre and within the 0 – 3 m depth range. The simulations used approximately 2 million numerical particles in total, each particle representing a fixed amount of Azamethiphos based on the data in Table 2.

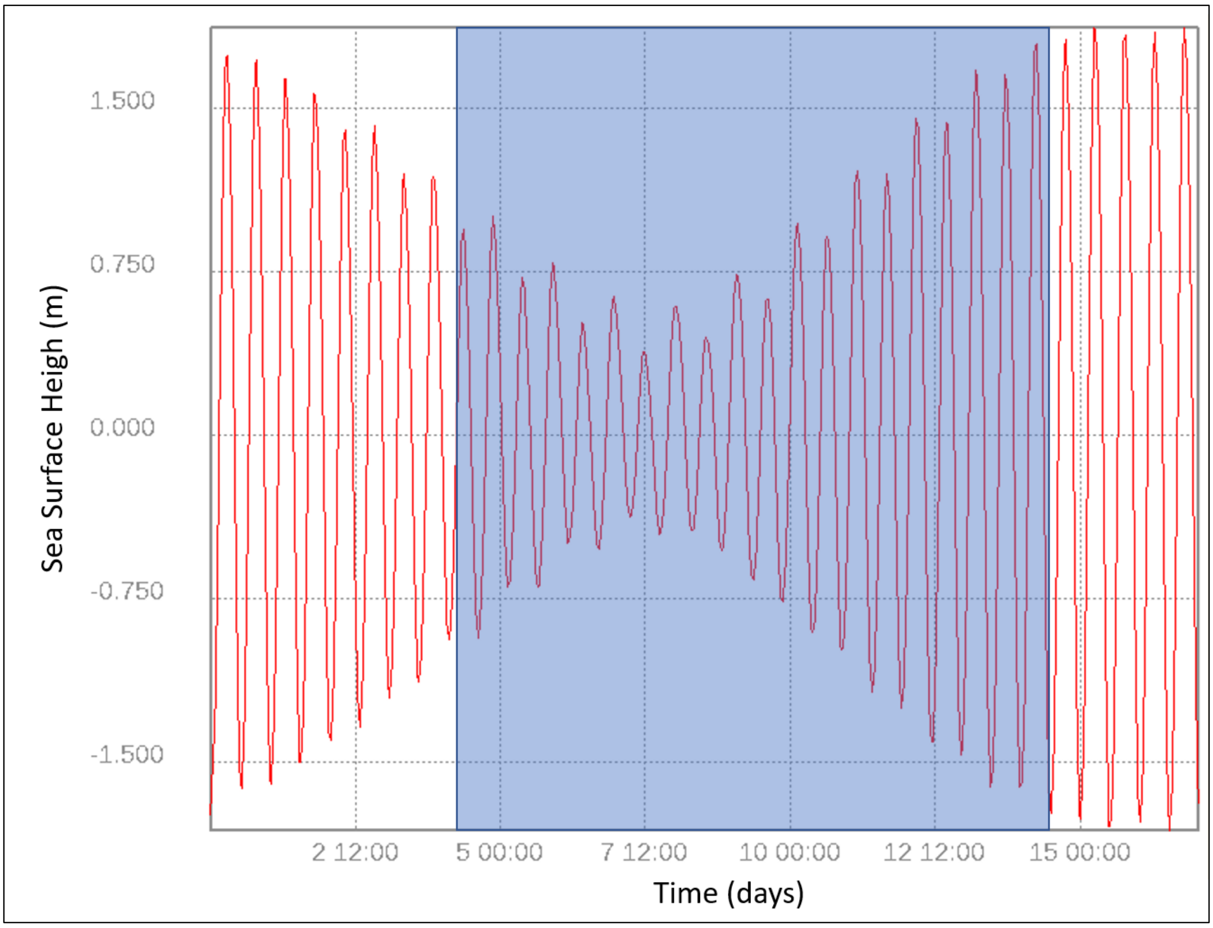
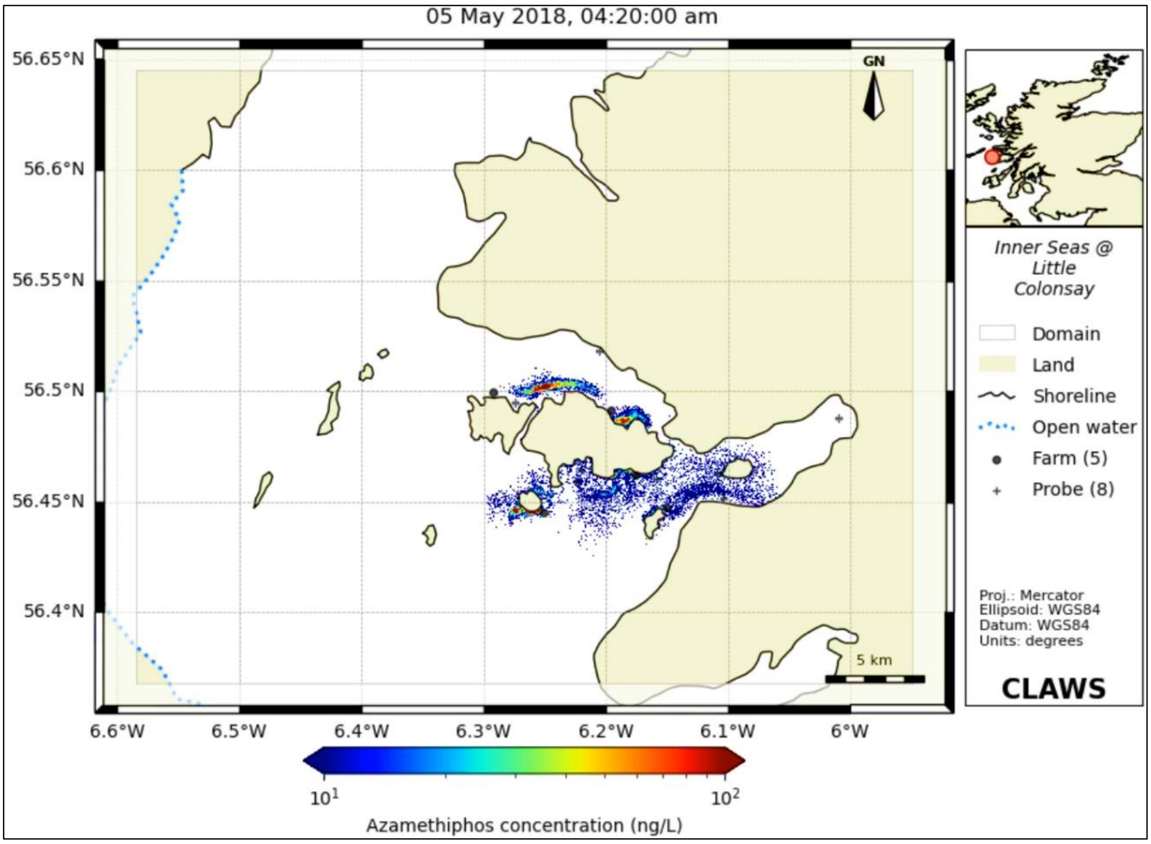


Figure 9 *Sea surface height (SSH) at Little Colonsay from 1st-30th May 2018. The pesticide dispersion simulation was performed over the period of 11 days from the 4th May 2018 covering the small neap tide cycle (blue).*

4. Results

4.1 *Dispersion patterns*

Figure 10 shows snapshots of the dispersion patterns of the ~2 million Azamethiphos particles as time progresses in the dispersion study. The dispersion patterns show that pesticide residues persist mainly in the inner seas around Little Colonsay with higher concentrations observed to the north of Ulva and Gometra. Some particles eventually exit the inner seas by flushing to the west and make their way northwards on the back of tidal pulses.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56.6°N
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6.5°W
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6.1°W
6°W
GN
5 km
Inner Seas @ Little Colonsay
Domain
Land
Shoreline
Open water
Farm (5)
Probe (8)
Proj.: Mercator
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Datum: WGS84
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CLAWS
10^1
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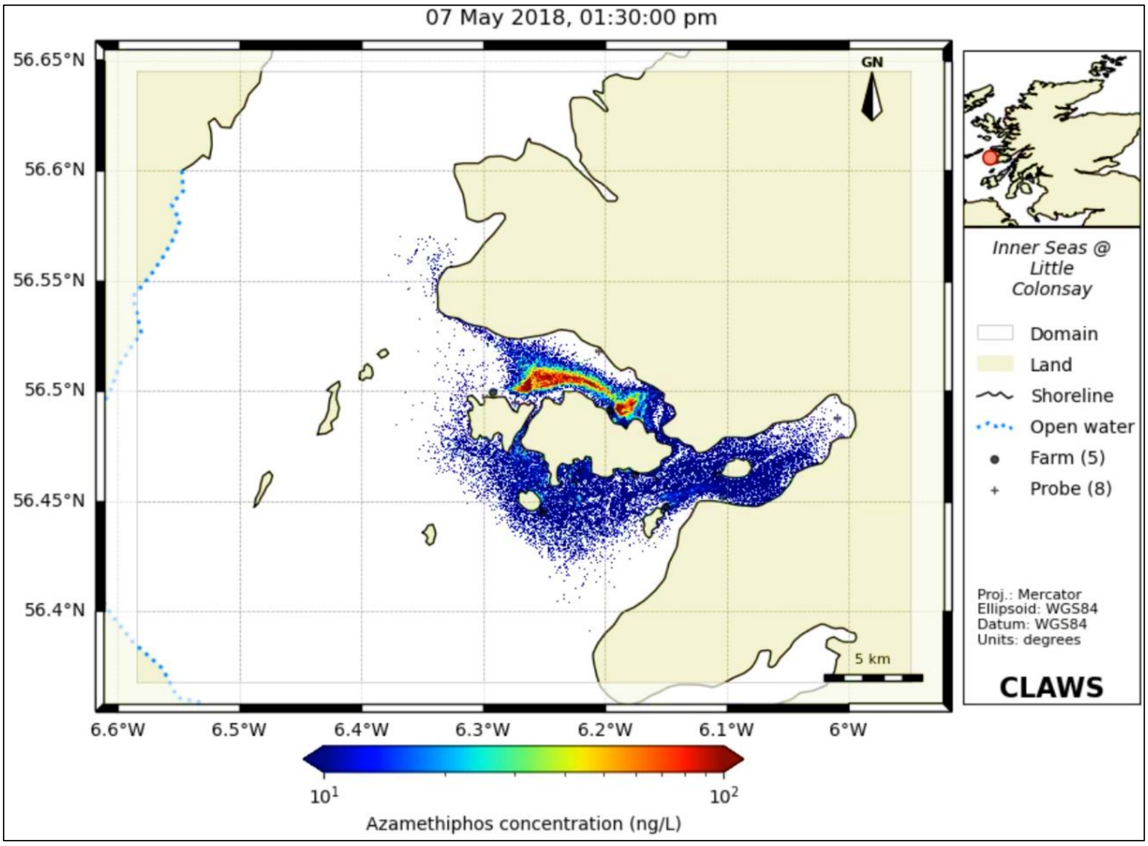
Azamethiphos concentration (ng/L)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56.6°N
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6.5°W
6.4°W
6.3°W
6.2°W
6.1°W
6°W
GN
5 km
Inner Seas @ Little Colonsay
Domain
Land
Shoreline
Open water
Farm (5)
Probe (8)
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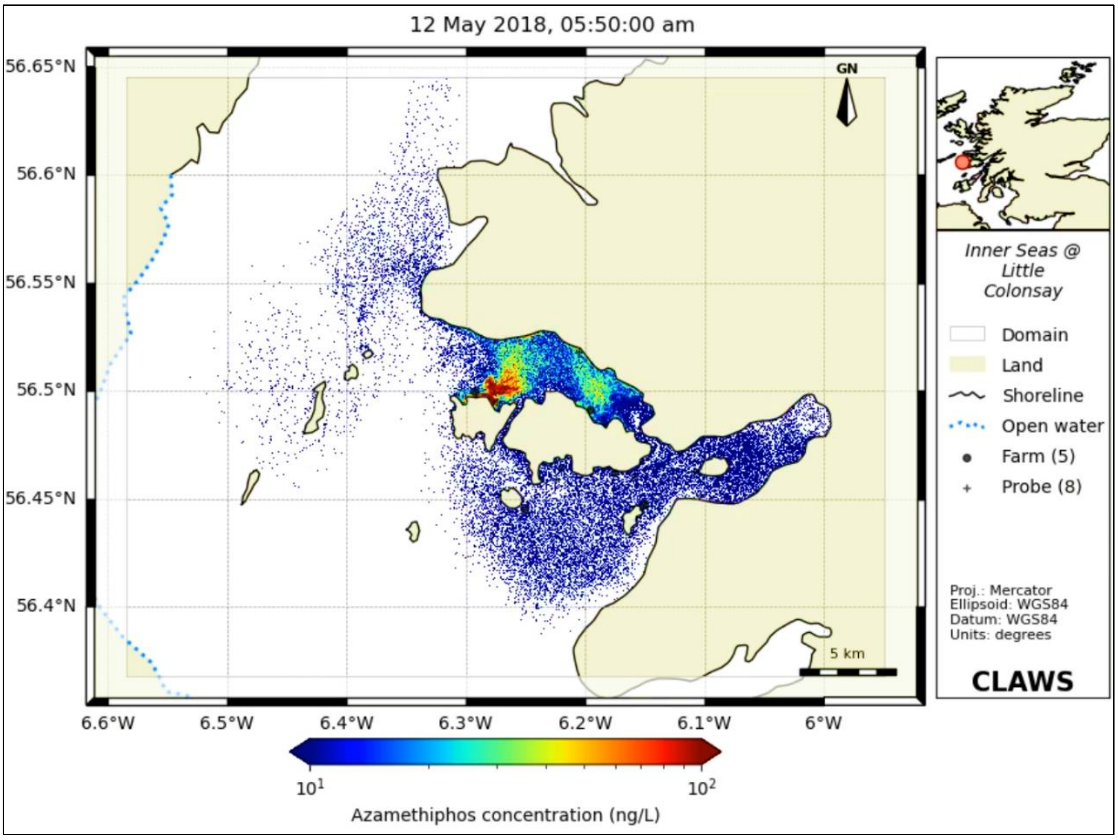
Ellipsoid: WGS84
Datum: WGS84
Units: degrees
CLAWS
10^1
10^2
Azamethiphos concentration (ng/L)



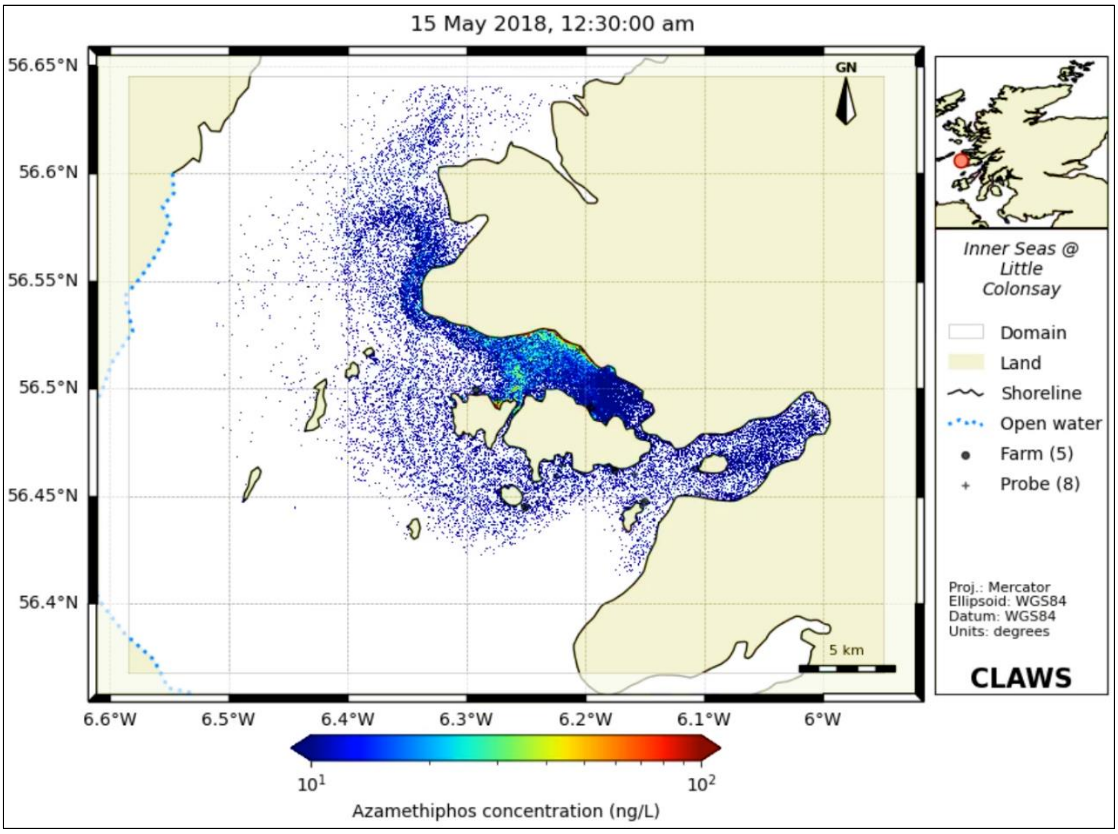


Figure 10 *Snapshots of Azamethiphos dispersion in the Little Colonsay system. Half-life of Azamethiphos = 8.9 days.*

4.2 *EQS and MAC evaluation*

As outlined in sections 3.2 and 3.3, time series of three metrics were constructed for the whole Azamethiphos dispersion simulation: (i) The peak concentration (ng/L) anywhere on the sampling grid; (ii) The area (km^2) where the EQS was exceeded; (iii) The area (km^2) where the MAC was exceeded. These results were used to assess whether the EQS or MAC was breached after the allotted period (72 hours after the final treatment).

Figure 11 shows the peak Azamethiphos concentration anywhere on the 20 m × 20 m × 3 m sampling grid. The graph shows that the 3-hour EQS (250 ng/L) is likely to be breached across the entire 11-day period of the dispersion. 3 days after the last treatment, both the 72-hour EQS and MAC are shown likely to be breached.

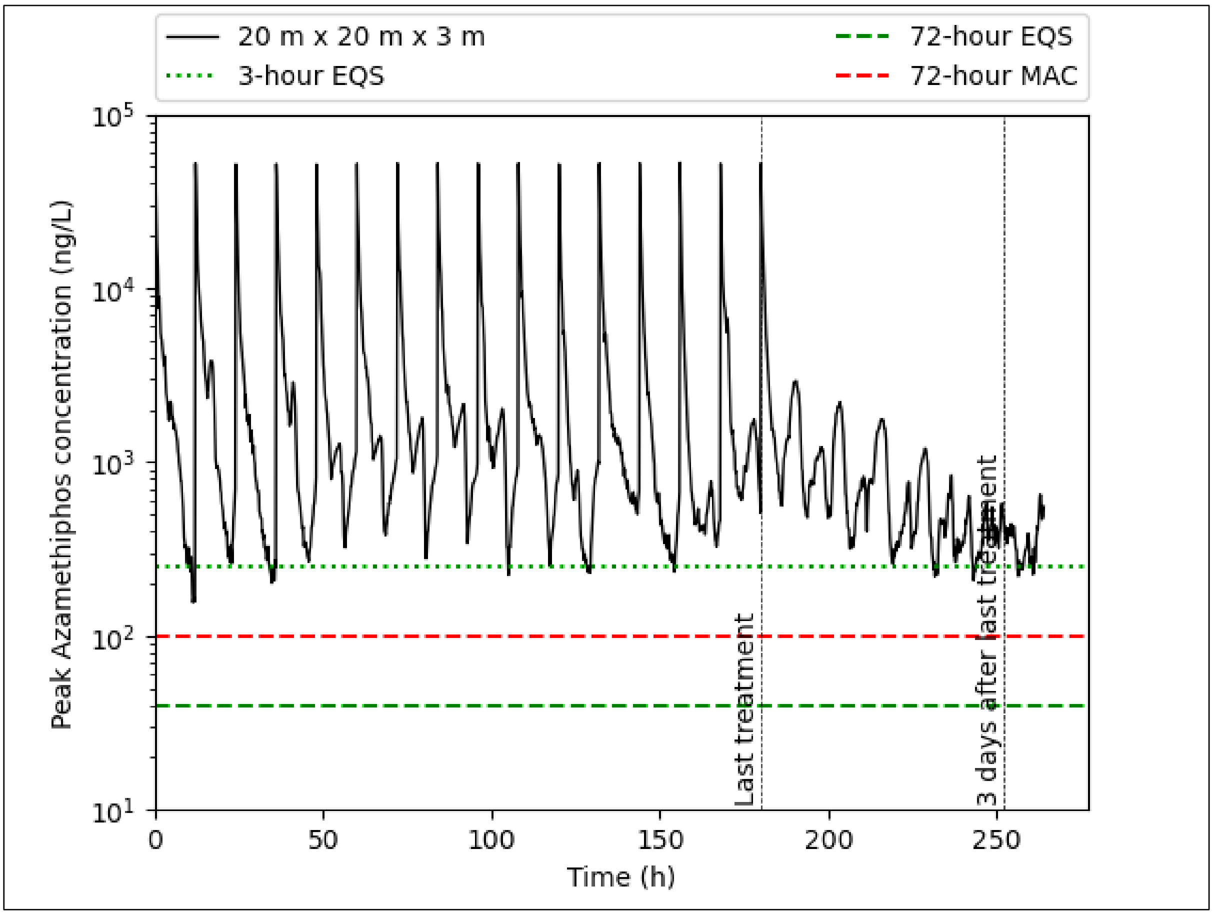


Figure 11 *Peak Azamethiphos concentration anywhere on the 20 m × 20 m × 3 m sampling grid. SEPA 3-hour EQS value is 250 ng/L, 72-hour MAC is 100 ng/L and 72-hour EQS is 40 ng/L. Half-life of Azamethiphos = 8.9 days.*

Figure 12 plots the area (km^2) exceeding the SEPA EQS (40 ng/L) for Azamethiphos. It is evident that throughout the entire 11-day dispersion simulation the area over the EQS (0.5 km^2) is likely to be exceeded.

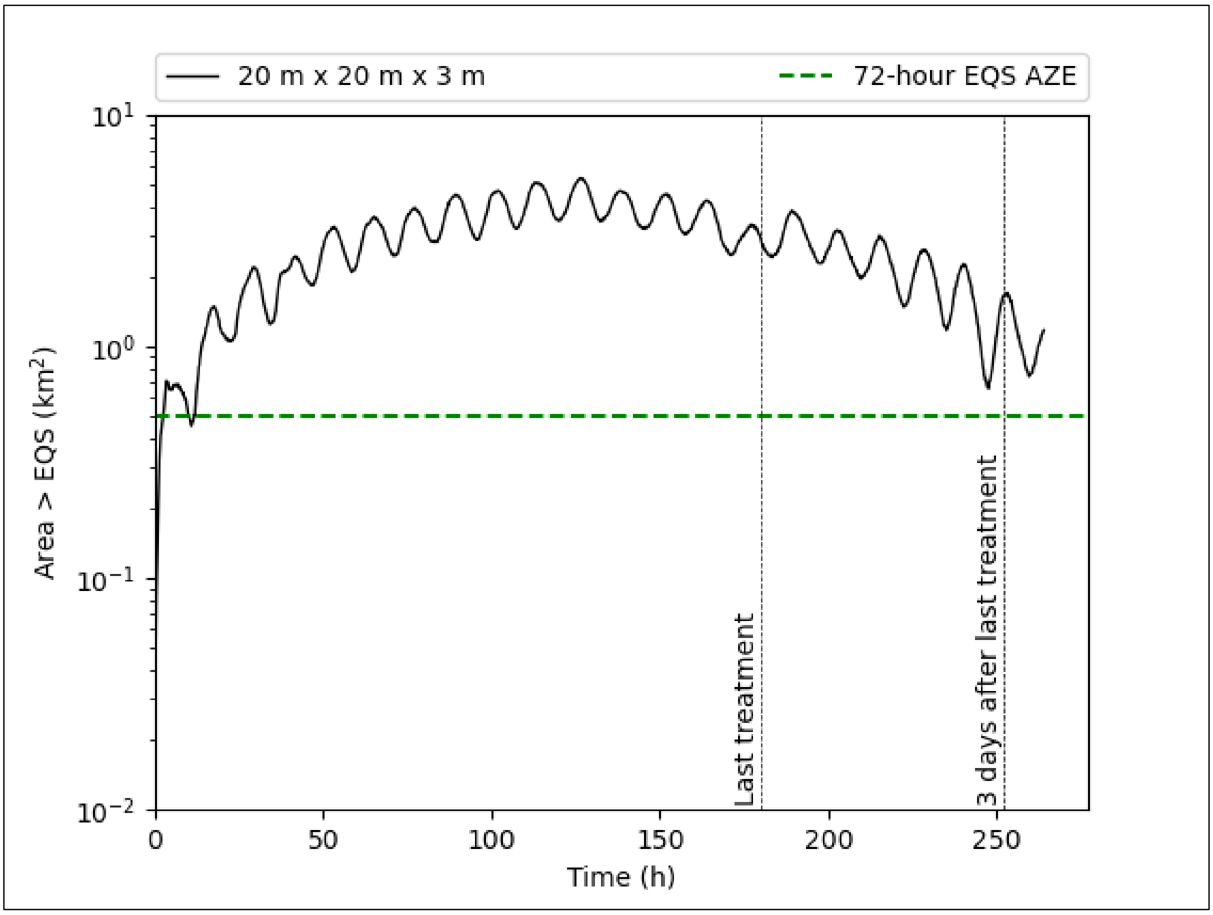


Figure 12 *Plot of area (km²) exceeding the SEPA EQS (40 ng/L) for Azamethiphos. The SEPA requirements state that this area must not exceed 0.5 km². Half-life of Azamethiphos = 8.9 days.*

Figure 13 plots the area (km^2) exceeding the SEPA MAC (100 ng/L) for Azamethiphos. The area over the MAC (0.5 km^2) is likely to be exceeded at certain times during the 7-day treatement period but then dissipates to fall below SEPA 0.5 km^2 threshold, 3-days after the final treatment.

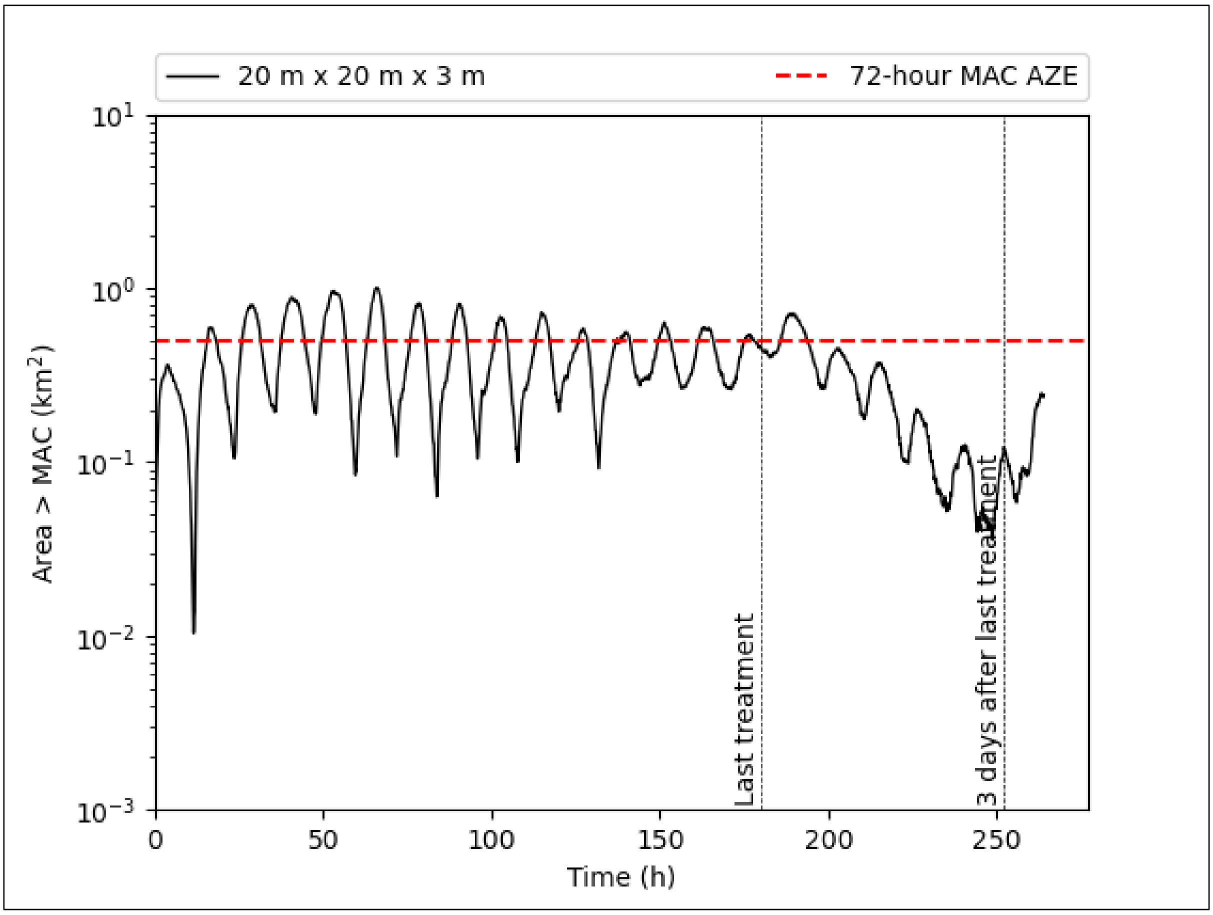


Figure 13 *Plot of area exceeding the SEPA MAC (100 ng/L) for Azamethiphos. The SEPA requirements state that this area must not exceed 0.5 km^2. Half-life of Azamethiphos = 8.9 days.*

4.3 *Azamethiphos concentrations at specific locations*

Virtual probes were placed locations around the inner seas at Little Colonsay to measure the Azamethiphos concentrations with time. The probe locations are shown in Figure 14.

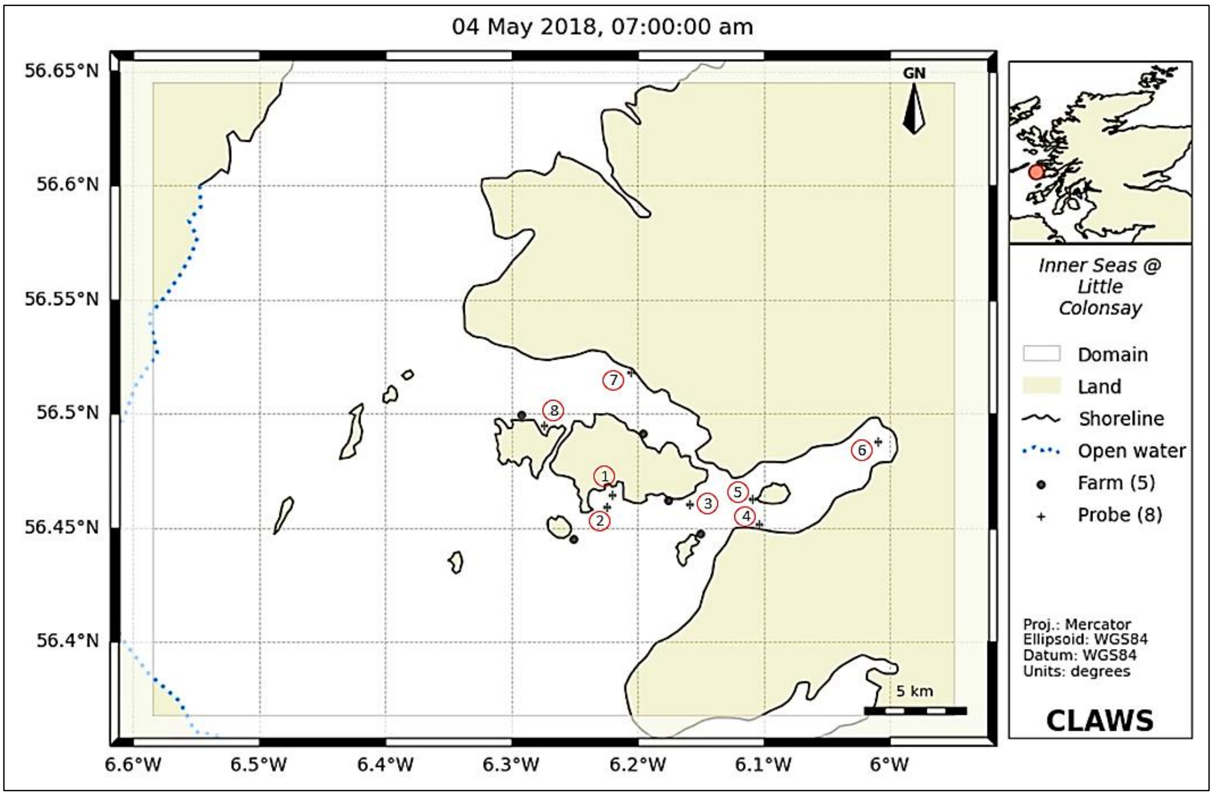


Figure 14 *Locations of virtual probes to measure Azamethiphos concentrations across the inner seas around Little Colonsay. Half-life of Azamethiphos = 8.9 days.*

Figures 15-22 show the results of Azamethiphos concentration with time for each of the probe locations. For probes 1-6, concentration levels of the order of 10 ng/L are likely to be encountered with a peak value of 100 ng/L occurring at probe 2 after approximately 65 hours from the beginning of the pesticide treatment.

For probe 7, Azamethiphos concentrations in excess of the EQS value of 40 ng/L are shown to be likely to occur frequently from 150 hours onwards. This pattern is repeated for probe 8 where the concentration is likely to exceed the EQS value at several instances and is also seen likely to breach the MAC value of 100 ng/L on 3 occasions from 150 hours onwards.

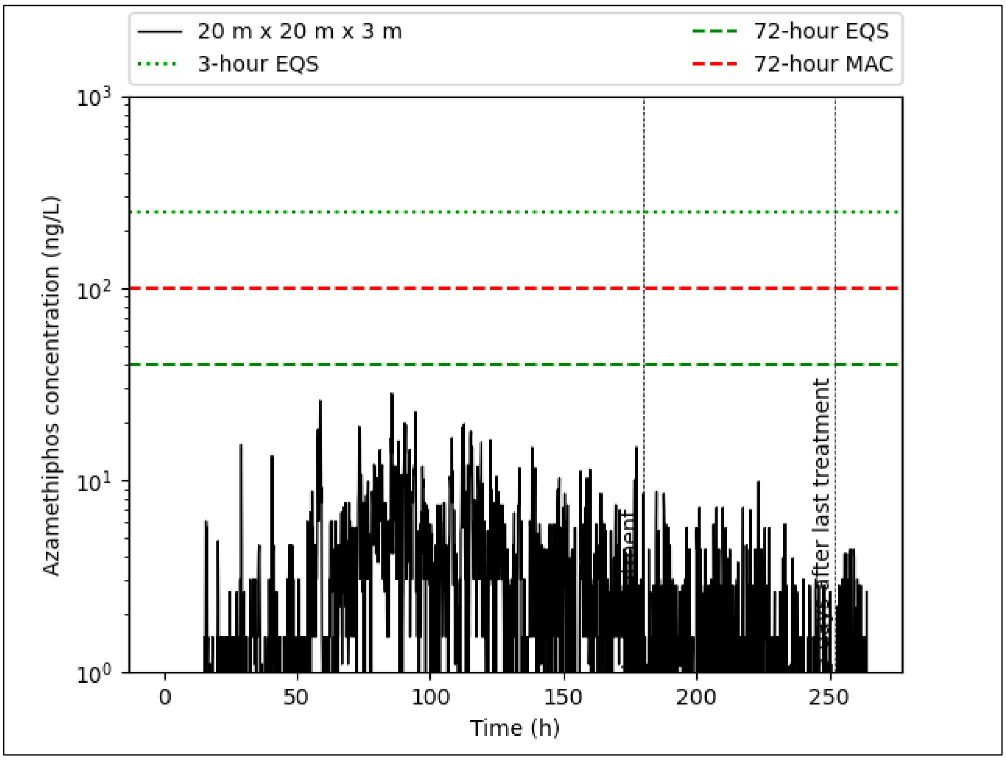


Figure 15 *Prediction of Azamethiphos concentration with time at Probe 1 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

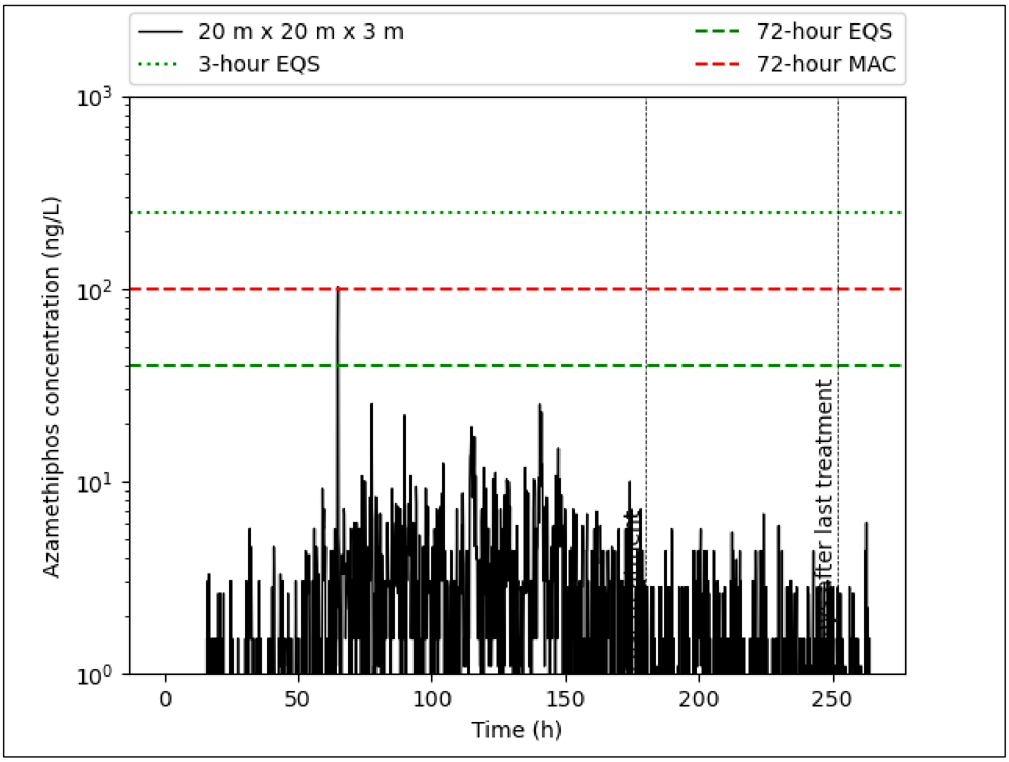


Figure 16 *Prediction of Azamethiphos concentration with time at Probe 2 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

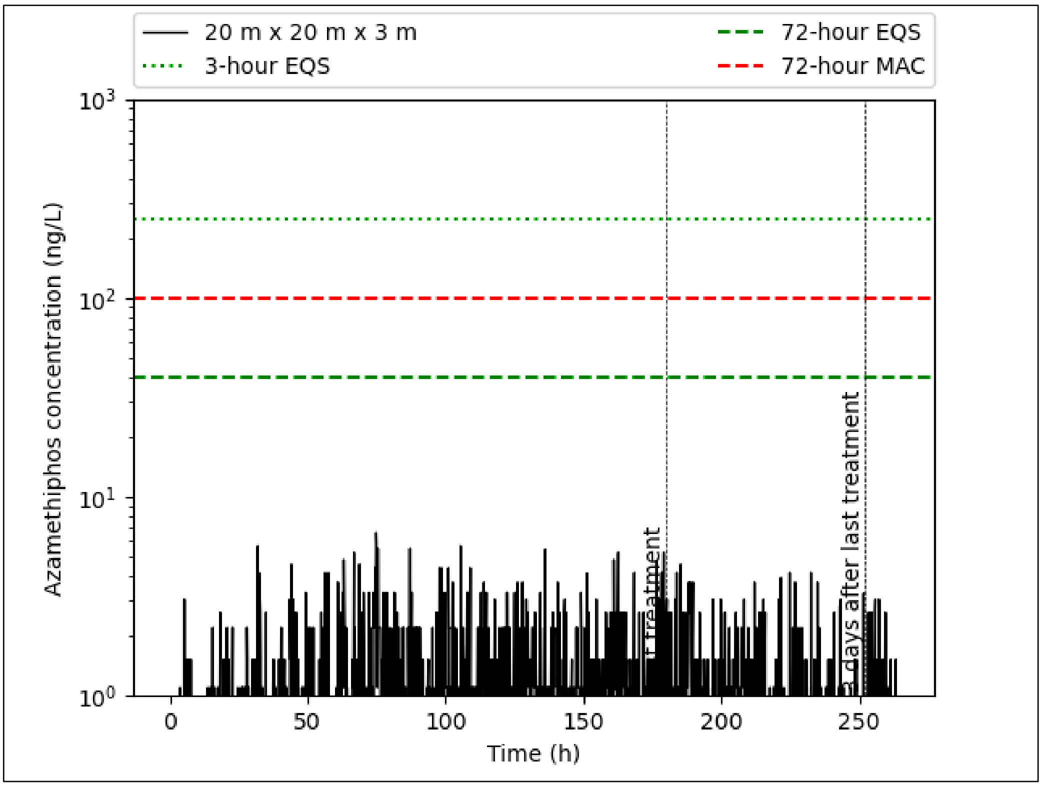


Figure 17 *Prediction of Azamethiphos concentration with time at Probe 3 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

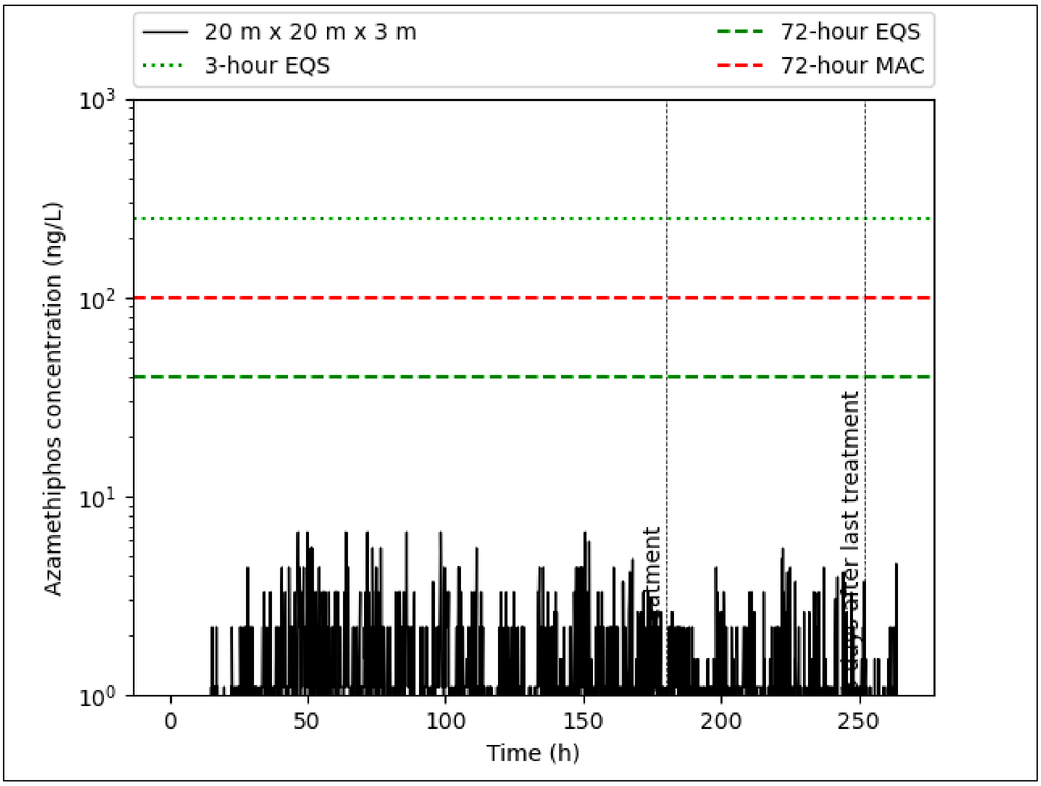


Figure 18 *Prediction of Azamethiphos concentration with time at Probe 4 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

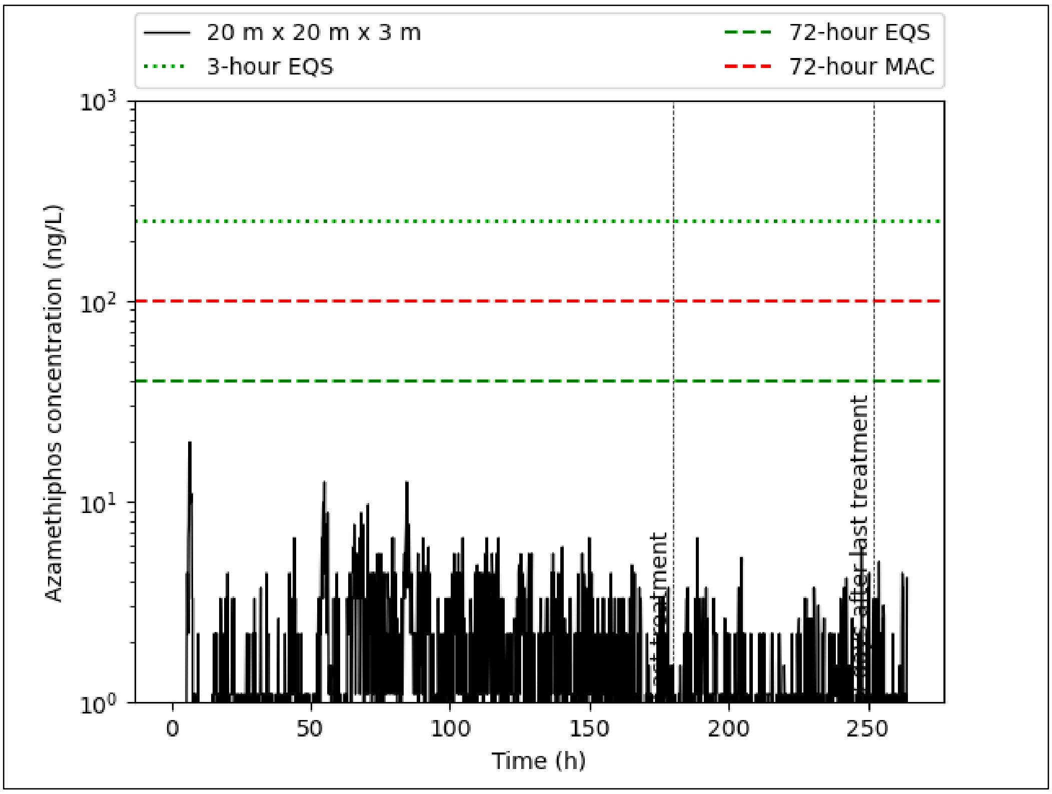


Figure 19 *Prediction of Azamethiphos concentration with time at Probe 5 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

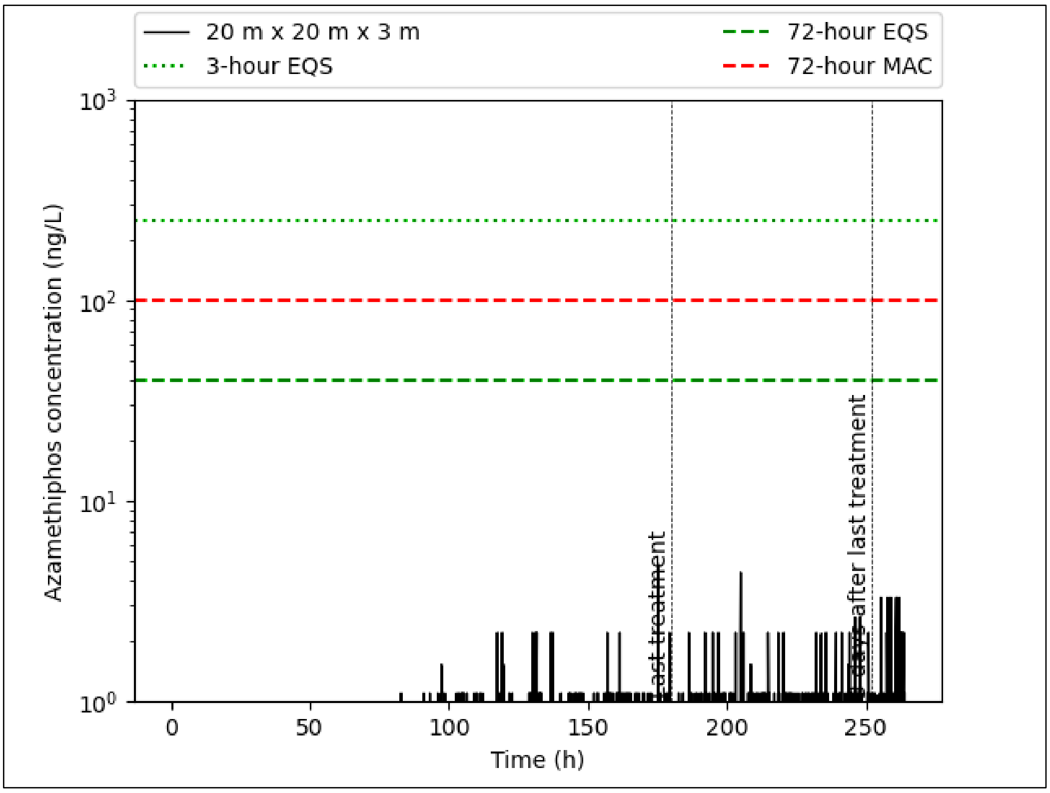


Figure 20 *Prediction of Azamethiphos concentration with time at Probe 6 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

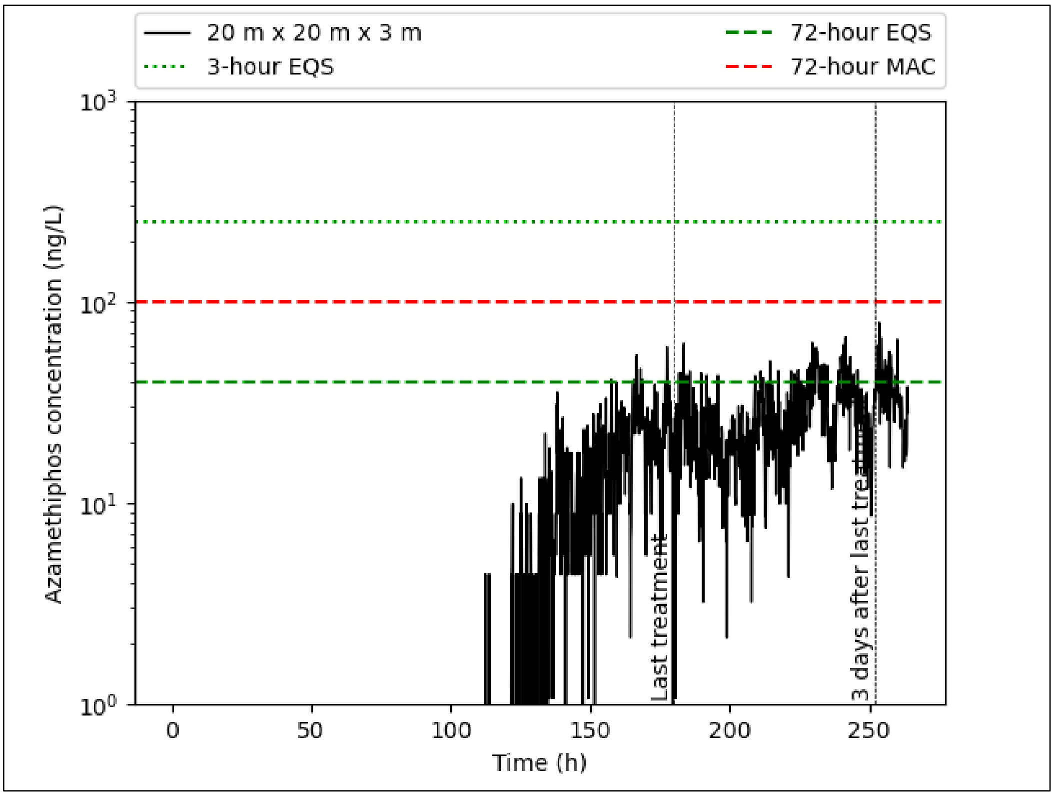


Figure 21 *Prediction of Azamethiphos concentration with time at Probe 7 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

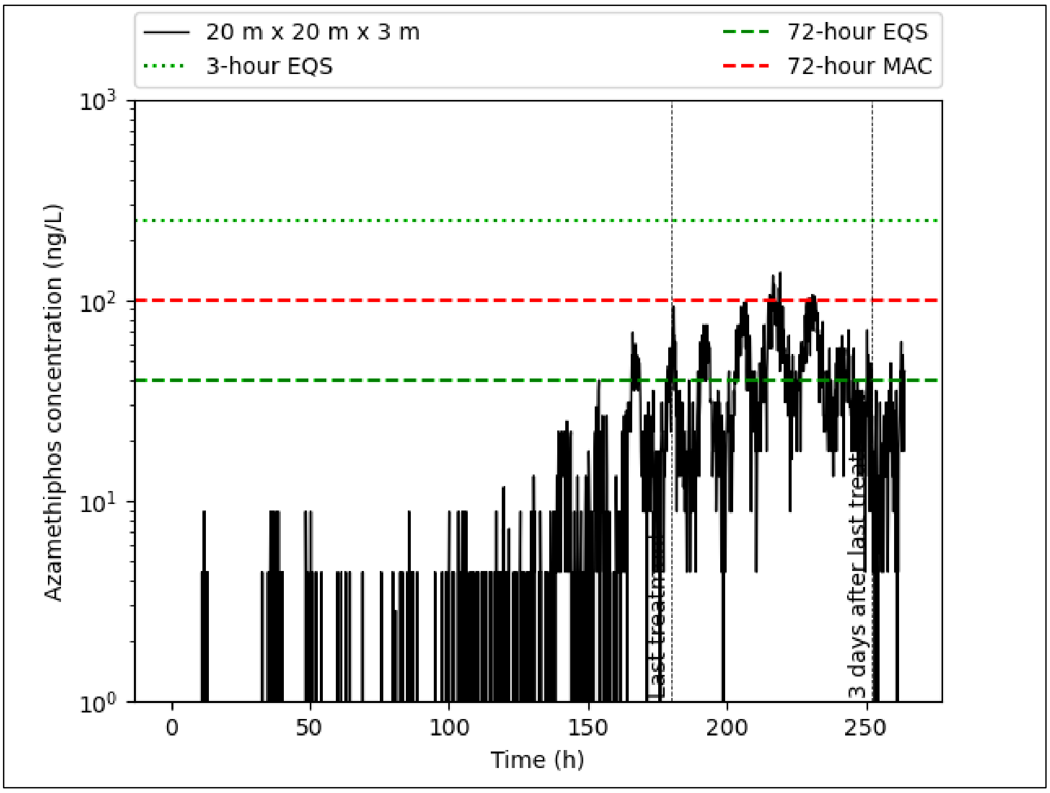


Figure 22 *Prediction of Azamethiphos concentration with time at Probe 8 (see Fig. 15 for probe locations). Half-life of Azamethiphos = 8.9 days.*

4.4 *Model sensitivity to half-life*

The results presented in this document were based on an Azamethiphos half-life value of 8.9 days. Similar runs were conducted using a half-life of 5.6 days and the results for concentration levels were broadly the same as those for 8.9 days with little discernible difference in the EQS and MAC outcomes. The 5.6 days half-life results are available on request.

5. Conclusions

A particle-based bath treatment model has been developed for application in salmon farms in semi-enclosed sea lochs and open sea areas. The bath treatment model is part of a suite of particle-based, open-source modules known as CLAWS – Chemicals, Lice and Waste from Salmon Farms [CLAWS, 2023]. The bath treatment model calculates the pesticide concentration in the marine environment and comparison is made against the statutory SEPA standards for Maximum Allowable Concentration (MAC) and Environmental Quality Standard (EQS). A 3D hydrodynamics model based on the Telemac code is used to drive the particle-based bath treatment calculation. The hydrodynamics model contains the influence meteorological forcing and stratification brought about by freshwater inflows and air-water heat exchange. For the Lagrangian particle-tracking, the open-source code OpenDrift [OpenDrift, 2023] has been used. Results show that the bath treatment code can successfully predict pesticide distributions and present the concentrations in a format suitable for scientific reporting. Pesticide dispersion patterns show that localised concentrations in excess of the MAC value of 100 ng/L in the inner seas north of Ulva and Gometra are likely to occur. Analysis of the results shows that the 3-hour EQS (250 ng/L) is likely to be breached across the entire 11-day period of the dispersion. 3 days following the final bath treatment, both the 72-hour EQS (40 ng/L) and MAC (100 ng/L) are shown likely to be breached. Throughout the entire 11-day dispersion simulation the area over the EQS (0.5 km^2) is likely to be exceeded. The area over the MAC (0.5 km^2) is exceeded sporadically but falls below the SEPA threshold level 3-days following the last bath treatement. Azamethiphos concentrations at specific locations around the inner seas at Little Colonsay show that peak concentrations in excess of the EQS and MAC values are likely to occur.

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